Hearing Commencing 26 February 2024

Bundle 13 - Miscellaneous

Volume 13

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NHS Scotland Assure's Position on Approach to Research, Including Ventilation

1. This paper seeks to assist the Inquiry in considering the following paragraphs from the Closing Statement by Counsel to the Inquiry and is further to responses already provided by NSS its Closing Statement (280524 NSS Closing Statement Final):

"*462. The Chair may consider that further research requires to be conducted to ensure that national guidance is adequate, appropriate and has a robust scientific underpinning.*

463. The Chair may consider that any such research should address emerging areas including "equivalent air changes per hour" and new technologies (such as ultraviolet light) for which there is no national guidance in Scotland (cf. England: Bundle 13, vol 10, page 297).

464. Assure has a research engineering department. It is involved with Napier University in research into the healthcare built environment. It may be helpful for the Chair to receive submissions on the nature of this research to determine whether Assure should be left to progress with the matter of whether a wider review is required. It may be helpful to the Chair if the nature of the research being conducted was addressed further in the closing submissions on behalf of NHS NSS."

2. It is also pursuant to a direct request from Lord Brodie for submissions, made on 21 May 2024.

3. For clarification, in reference to Paragraph 464 of the Closing Statement by Counsel to the Inquiry, NSS note that the NHS Scotland Assure Research Service is multi-disciplinary in nature and not focused solely on engineering.

4. Healthcare built environment research is an ongoing, developing and multi-disciplinary subject. As such NHS Scotland Assure would always endorse a collaborative approach to research, to enhance the available evidence base, understand the impact on health and safety (including the impact on patient safety) and translate these into clinical, infection prevention and control, engineering, design and facilities management recommendations. NHS Scotland Assure would welcome recommendations from the Inquiry as to how research could be progressed in the future and would respectfully request to be part of any discussions that may shape how research is undertaken in the future, to ensure a collegiate and transparent approach is maintained. This will help to ensure that research outcomes continue to be reflected in guidance and operational good practice. The extent to which NHS Scotland Assure can progress research is limited by the funding allocated to the organisation by Scottish Government.

5. The NHS Scotland Assure Research Service works with subject matter experts ranging from academic professionals, NHS staff and wider industry experts to develop the evidence base and to support the Service's advice and guidance. This is progressed in two ways; through the review of the extant evidence via literature review and by supporting development of new evidence through the

commissioning of research. Research can either be commissioned through the Edinburgh Napier University Fund or through NHS Scotland Assure direct funding (derived from the funding allocated to the organisation by Scottish Government).

6. NHS Scotland Assure have outlined within this paper historic research which underpins existing ventilation guidance in addition to current research being progressed. The paper also outlines current areas being considered for future research, as part of the research service requirement to "horizon scan" to inform priorities. As new risks emerge, NHS Scotland Assure will reflect on the need for further research and reprioritise any existing research as required.

7. The paper primarily addresses research associated with ventilation, NHS Scotland Assure note that its research service is also undertaking works on other aspects of the healthcare built environment including water and sustainability.

8. Whilst this paper outlines historic, ongoing and potential future research into ventilation in the healthcare built environment, NHS Scotland Assure would welcome any recommendations for future research which may assist the organisation in identifying, informing and prioritising future research workstreams. In particular NHS Scotland Assure support any research that provide further linkage between scientific research and patient outcomes (in other words, further the understanding of the real world effects of ventilation research).

9. NHS Scotland Assure would also note its support to any research that may mitigate built environment risks across any subject matter, this is not restricted solely to ventilation. A recent example of directly funded NHS Scotland Assure research is a project examining "The role of air pressure transients on the spread of bacteria from water trap seals in clinical settings", which was undertaken in conjunction with Heriot Watt University.

10. Further information on healthcare built environment research commissioned via the NHS Scotland Assure Research Service can be found on the NSS website: https://www.nss.nhs.scot/nhs-scotland-assure/research-development-and-innovation/research-portfolio/.

Scientific Basis for Existing SHTM & HBN Ventilation Guidance

11. In response to paragraph 462 of the Closing Statement by Counsel to the Inquiry, "*The Chair may consider that further research requires to be conducted to ensure that national guidance is adequate, appropriate and has a robust scientific underpinning.*" NHS Scotland Assure would note that there is a variety of research and subject matter expert opinion available that underpins the principals and technical intent of existing ventilation guidance. The Inquiry has received evidence from ventilation subject matter experts[1-4] in this respect and to further assist the Inquiry, NHS Scotland Assure have noted examples of further published research in this field[5-9].

12. Whilst this research was not undertaken directly by NHS Scotland Assure, in many instances this has been used to inform national guidance documents adopted by the devolved administrations, including SHTM 03-01 and SHPN 04-01. NHS Scotland Assure would also note that many of the academic experts responsible for undertaking research in this field have been part of the development and consultation process for creating the national engineering technical guidance. including SHTM 03-01.

13. Air change rates are one of the many healthcare engineering and design criteria which impact on the quality of indoor air, and the outcomes associated with it including infection transmission rates. Air change rates should be considered as one of a series of infection prevention and control measures and not be considered in isolation. Air change rates is a complex topic, mainly due to the multifactorial nature of indoor healthcare environments and the challenge of translating research curated in laboratories into live environments. There is limited definitive research in this field linked to how air change rates may impact on patient and clinical outcomes.

14. Much of the published literature which considers ventilation during infection transmission events within heath and care settings is impacted by confounding factors making it difficult to establish any real evidence of an absolute link to the healthcare ventilation system. For example, much of the published outbreaks are observational outbreak reports in which ventilation has been considered as a factor in the transmission but it is impossible to identify it as a definitive causal factor. Examples of confounding factors include but are not limited to; presence or absence of symptoms, types of procedures being carried out on the patient, the infectious dose of the pathogen concerned, immunosuppression of the patients.

15. There are ethical challenges (for example potential exposure to harmful pathogens and agents) with respect to comparing ventilation system performance and the consequential impact on clinical and patient outcomes, particularly when considering for example dilution effects on live viruses (i.e. how air may be used to reduce the concentration of a particular pathogen or agent). Consequently, much of the research has been based on computational fluid dynamic (CFD) studies (examples of which are cited earlier in this paper), which can often be difficult to replicate in a “real life” scenario due to the complexities noted above.

16. The NHS Scotland Assure Research Service also commissioned research into Far UVC light for reducing airborne transmission of bacteria and viruses[10]. This has supported NHS Scotland Assure to input into discussions into the formation of new guidance, such as the UVC air cleaning devices guidance, in addition to informing future research topics, both of which are noted later in this paper.

The Need for Further Research on Air Change Rates

17. The “mechanical” performance of a ventilation system in respect to air changes is well established. As noted above in paragraph 8, (research into the impact a ventilation system has on patient and clinical outcomes, in the view of NHS Scotland Assure, does merit future research (noting comments in paragraph 15 about ethical challenges). NHSS Assure does not yet have a specific research project or projects in mind, we are supportive of research into this area, reflected in our priority research topics. We favour a collegiate approach, with multi-disciplinary experts including academics, clinicians, engineers and industry/manufacturers. It should be noted that due to the complexities involved and multiple confounders which exist in a live clinical environment, including human factor variables, it may not ever be possible to determine an absolute air change rate which eliminates risk.

Status of UV Guidance & Portable HEPA Devices in Scotland

18. In response to paragraph 463, *“The Chair may consider that any such research should address emerging areas including “equivalent air changes per hour” and new technologies (such as ultra violet light) for which there is no national guidance in Scotland (cf. England: Bundle 13, vol 10, page 297)”*. NHS Scotland Assure note that whilst it has not published equivalent guidance in Scotland, health boards can utilise the published guidance at their discretion as required. This is not an uncommon approach and helps to ensure that there remains a unified approach to the production of technical engineering guidance between Scotland, England, Wales & Northern Ireland. NHS Scotland Assure are also in dialogue with colleagues in the rest of the UK on how this approach can evolve for engineering technical guidance in the future, for example a “unified” HTM 03-01 without the requirement for locally published variants.

19. NHS Scotland Assure were part of the NHS England working group responsible for the production of guidance on portable HEPA devices and UVC air cleaning devices. These were referred to, and provided with, the ‘Closing Statement by National Services Scotland Re hearings commencing on 26 February 2024 (Royal Hospital for Children and Young People / Department of Clinical Neurosciences).’

20. NHS Scotland Assure, in conjunction with the Scottish Engineering and Technology Advisory Group (SETAG) and the National Heating & Ventilation Advisory (NHVAG) group are currently updating SHTM 03-01 Ventilation for healthcare premises, which will formally make reference to the above guidance documents – NHS Scotland Assure aim to publish this in 2024.

NSS Scotland Assure – Position on Equivalent Air Changes Per Hour & New/Emerging Technologies (e.g. UV)

21. NHS Scotland Assure consider that continued research is required to understand in more detail potential benefits and risks associated with devices that provide "equivalent air changes". The concept of "equivalent air changes" is based upon recirculation of air within a space through an air cleaning device (or similar).

22. With respect to new and emerging technologies, NHS Scotland Assure consider that continued research is required to understand in more detail potential benefits and risks associated with the implementation of devices. For example, when considering the use of UV technologies as a method to reduce the risks of airborne contaminants impacting on air quality, system efficiencies must be considered – systems will only be as effectives as the percentage of total air volume within the space that is "processed" through the UV technology device. The behaviour of air is complex and much of the research to date has been based on CFD simulations – a further assessment of "real life" scenarios for example would be beneficial.

NHS Scotland Assure – Current and Future Ventilation Research

23. In response to paragraph 463, "*The Chair may consider that any such research should address emerging areas including "equivalent air changes per hour" and new technologies (such as ultra violet light) for which there is no national guidance in Scotland (cf. England: Bundle 13, vol 10, page 297)*". The table below outlines research topics identified by NHS Scotland Assure on the subject of ventilation for further exploration, refinement and prioritisation in FY24/25 and beyond. These are predominantly developed by colleagues from ARHAI Scotland and the Engineering team and consider feedback from key stakeholders including national strategic groups e.g. Scottish Engineering & Technology Advisory Group (SETAG), as well as through dialogue with external colleagues such as academic colleagues and industry partners. Refinement of priorities for individual topics is informed by a systemic literature review.

Topic
Air quality monitoring in the Healthcare Built Environment
Air Change Rates
Ultraviolet - C (UVC) applications in the Healthcare Built Environment
Grille Selection & Impact on Ventilation Efficiency in the Healthcare Built Environment
Natural Ventilation in the Healthcare Built Environment
Thermal Wheels
The Use of High Efficiency Particulate Air (HEPA) Filters in Intensive Care Units (ICU)
Patient Cohorts Where Low Humidity is a Concern
Open plan treatment area ventilation design
Isolation Suite Ventilation Systems
Review of Emerging Ventilation Technologies and Appropriateness for Use in the Healthcare Built Environment

24. NHS Scotland Assure are currently undertaking a systematic literature review, led by ARHAI, on ventilation which will consider the following questions (NB: these questions may change as a result of the consultation process):

- Which patient populations are considered to be at increased risk of infection or colonisation with air transmitted infectious agents of environmental origin?
- Which air transmitted infectious agents of environmental origin are responsible for healthcare associated infection or colonisation?
- What types of healthcare associated infection are associated with air transmitted infectious agents of environmental origin?
- What are the incubation periods for healthcare associated infections involving air transmitted infectious agents of environmental origin?
- What are the known or suspected transmission routes for air transmitted infectious agents of environmental origin in health and care settings?
- Which clinical procedures are associated with an increased risk of transmission of air transmitted infectious agents of environmental origin?
- What are the environmental causes/sources of infectious agents in the air of health and care settings?
- When should environmental testing be carried out in healthcare settings?
- How should environmental testing be carried out in healthcare settings?
- Whose responsibility is it to analyse and interpret environmental testing results?
- What are the acceptable limits for environmental testing within the healthcare setting?
- What actions should be undertaken to reduce the risk of healthcare associated infection/colonisation with air transmitted infectious agents of environmental origin?
- What are specific IPC considerations for water ingress in health and care settings?
- What are specific IPC considerations during periods of active healthcare construction or renovation?
- How are healthcare associated incidents involving air transmitted infectious agents of environmental origin recognised and defined?
- How should healthcare associated incidents involving air transmitted infectious agents of environmental origin be investigated and by whom?
- How should healthcare associated incidents involving air transmitted infectious agents of environmental origin be assessed, reported and escalated locally and nationally?
- What control measures should be implemented when managing healthcare associated incidents involving air transmitted infectious agents of environmental origin?

25. This work commenced in July 2023 and is scheduled to complete March 2025. The question set above and accompanying proposed search strategy is currently out to consultation with stakeholders. Once agreed, the literature search will commence and articles will be screened, critically appraised using

SIGN50 methodology and AGREE tool and recommendations can then begin to be formulated. The findings of the literature review will contribute towards further development of chapter 4 of the National Infection Prevention and Control Manual (NIPCM). Should any gaps be identified in the literature review, further research will be considered and scoped by NHS Scotland Assure to inform future research workstreams. The findings will also be considered in future iterations of engineering technical guidance, including SHTM 03-01.

26. Further information on the ARHAI literature development methodology[11] can be found in the National Infection Prevention and Control Manual.

NHS Scotland Assure & Edinburgh Napier University Research Fund

27. NHS Scotland Assure have secured funding (Funding for commissioning research was secured by the Senior Responsible Officer for the Centre of Excellence Programme (prior to the launch of NHS Assure) from NSS) to progress Built Environment Research. Allocation of these funds is being overseen by the NHS Scotland Assure commissioning partner Edinburgh Napier University. Edinburgh Napier University was initially contracted for two years, and this was extended for a further year until March 2025. Funds are available for research aimed at improvement of risk management and quality in the healthcare-built environment across NHS Scotland. Progressed research will seek to minimise risk in our healthcare buildings and environments, protecting patients from the risks including transmission of infection, and supporting better outcomes for patients in Scotland.

28. Information regarding the current scope of research projects being taken forward through the Napier Fund can be found here:

    https://www.napier.ac.uk/research-and-innovation/business-and-innovation-hub/innovate-with-us/joint-research-and-innovation/funding-support/nhsscotland-assure-research-service

29. NHS Assure has used the Napier fund to both encourage and select the best research projects for progression to potentially support guidance and advice.

30. At the time of writing, NHS Scotland Assure note that no research is currently active, however it is envisaged that research projects will commence within the next three months pending finalisation of the terms and conditions between Edinburgh Napier University and the research groups.

31. These include:

    - A project examining potential test methods to measure the aerosolised respiratory virus exhaled from infected patients admitted to hospital and identify the factors which determine how much virus would be exhaled as aerosols with a focus on environmental transmission.

- A project examining the use of environmental sensors to enable real-time monitoring of ventilation in hospitals (e.g. CO_2) to raise awareness, inform decision making and support action to improve indoor air quality (IAQ), and indirectly reduce risk of infections to staff and patients.

32. As part of the Napier Research Fund Governance, any proposal will be subject to a review process by a multidisciplinary assessment panel. The panel is made up of academic, subject matter and operational experts who will review the applications made and consider whether the proposed research projects would be appropriate to be progressed through the fund.

33. A flowchart of the application process is provided for the Inquiry's reference[12].

34. Additionally, NHS Scotland Assure supports year-on-year research activity within its directly llocated resources.

References

1. Expert Report by Dr Shaun Fitzgerald - Ventilation Principles – Evidence to Scottish Hospitals Inquiry, Bundle 6 – Expert Reports and Statements reference A37277147.

2. Expert Report by Professor Hilary Humphries - Evidence to Scottish Hospitals Inquiry, Bundle 6 – Expert Reports and Statements reference A37331867.

3. Expert Report by Stephen Maddocks - Evidence to Scottish Hospitals Inquiry, Bundle 6 – Expert Reports and Statements reference A37465696.

4. Statement by Andrew Poplett - Evidence to Scottish Hospitals Inquiry, Bundle 6 – A37517821

5. Appraising healthcare ventilation design from combined infection control and energy perspectives. Catherine J. Noakes, P. Andrew Sleigh & Amirul Khan. August 2012. https://www.tandfonline.com/doi/abs/10.1080/10789669.2011.592054

6. Mathematical models for assessing the role of airflow on the risk of airborne infection in hospital wards. Catherine J. Noakes, P. Andrew Sleigh. October 2009. https://royalsocietypublishing.org/doi/abs/10.1098/rsif.2009.0305.focus

7. The ventilation of multiple-bed hospital wards: Review and analysis. Clive B. Beggs PhD, Kevin G. Kerr MD, Catherine J. Noakes PhD, E. Abigail Hathway MEng , P. Andrew Sleigh PhD. May 2008

   https://www.sciencedirect.com/science/article/pii/S0196655307008000

8. Modelling the transmission of airborne infections in enclosed spaces. C. J. NOAKES, C. B. BEGGS, P. A. SLEIGH and K. G. KERR. February 2006

https://www.cambridge.org/core/journals/epidemiology-and-infection/article/modelling-the-transmission-of-airborne-infections-in-enclosed-spaces/40DFA4922A77116E6E4460F6A25FD36D

9. Assessing the effects of transient weather conditions on airborne transmission risk in naturally ventilated hospitals. Alexander J Edwards, Martin Lopez-Garcia, Daniel Peckham, Marco-Felipe King. March 2024.

   https://www.researchgate.net/publication/378720902_Assessing_the_effects_of_transient_weather_conditions_on_airborne_transmission_risk_in_naturally_ventilated_hospitals

10. Far UVC light for reducing airborne transmission of bacteria and viruses. Final report for NHS Scotland Assure Project Assure Research 21-0001. Kenny Wood, Catherine Adamson, Camilo Penaloza, University of St Andrews Ewan Eadie, Ninewells Hospital, Dundee Catherine Noakes, Louise Fletcher, Waseem Hiwar, Emma Tidswell, University of Leeds David Brenner, Columbia University

11. National Infection Prevention and Control Manual: Methodology. Version 4.1, 25 January 2024

12. Edinburgh Napier University – NHSSA Research Fund Application Review Process Diagram

Appraising healthcare ventilation design from combined infection control and energy perspectives

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ABSTRACT

This paper considers an approach for assessing the balance between energy use and infection control in hospital ward ventilation by combining a stochastic disease outbreak model with a cost evaluation. Disease dynamics are simulated using a Susceptible-Exposed-Infector-Removed (SEIR) infection modelling approach, with the contact rate due to airborne transmission incorporated through coupling with the Wells-Riley model. Results presented for a hypothetical ward scenario demonstrate that stochastic effects in a small population, such as a hospital, are a controlling factor in the risk of an outbreak and that conventional deterministic models may give misleading results. Cost appraisals clearly show the trade-off between ventilation provision and infection risk depends on many factors including the disease characteristics, people concerned, ventilation system design and rate and the costs of both providing ventilation and treating infections. Although limitations in the input data currently reduce the robustness of the outputs, the approach is shown to be a useful framework for a tool that can quantitatively assess ventilation design from different perspectives for healthcare environments. The paper also highlights some of the knowledge required from further research to enable better quantification of the behaviour of pathogens and the transmission processes for hospital infections.

INTRODUCTION

The choice of ventilation system for hospital environments is influenced by many factors. High risk environments, such as isolation rooms, operating theatres and pharmaceutical areas, are generally dominated by infection concerns with this driving the ventilation agenda. For example in the case of airborne infection isolation rooms, and the provision of a high airflow rate to ensure dilution of pathogens within the room and an appropriate pressure regime to limit transfer of pathogens between the room and neighbouring spaces, delivered by a mechanical means, tends to be the ventilation system of choice (Booth et al. 2009). Depending on the application and level of risk, fine particle filtration or other air disinfection techniques may be employed on the supply and/or extract air (Department of Health 2007, Jensen et al. 2005). Ventilation is also driven by the infection control agenda in operating theatre environments with the complexity of the system increasing with risk. At the highest end, Ultra Clean Ventilation theatres for high risk surgery such as orthopaedics have downflow air movement of up to 0.6 m/s (1.97 ft/s) in the central zone (Friberg et al. 2002) with room airflow circulated through ceiling mounted High Efficiency Particulate (HEPA) filters to provide a constant velocity downflow region over the operating area (Chow and Yang 2004). While factors such as energy use and plant size will be considered during design, they are generally not the primary drivers in the specification of these specialised ventilation systems. In both these cases air flow rates, pressure differentials and levels of air cleaning generally increase with the likely risk in the environment. Clearly this will substantially increase costs but on the whole is easily justified by the better clinical outcomes for the patients. For example the ventilation costs for an immune-compromised transplant patient who requires positive pressure isolation with a HEPA filtered supply after surgery are likely to be minor compared to the clinical costs of carrying out a transplant.

However in most patient environments such as wards, waiting areas, outpatient clinics and treatment rooms the most appropriate ventilation design is not so clear cut. In this case the thermal comfort of patients and the energy performance of the system are seen as equal, if not more important concerns than the transmission of infection. Balancing these demands is typically tackled by a broad guidance approach, using generic ventilation rates and comfort temperatures set out in national documents (Department of Health 2007) and the choice of mechanical or natural ventilation determined by local conditions, other elements of the building design and the expertise of those designing the system. The resulting ventilation, while probably adequate will generally have no formal evaluation that considers the balance between infection control, comfort and energy. As ventilation for infection control is associated with airborne transmission, this on the whole takes a back seat as most infections in general patient environments are regarded as being contact borne. However there is increasing evidence that the transport of pathogens through the air is linked to many common healthcare acquired infections (HCAI's) that are not regarded as airborne infections.

In recent years several studies have linked Methicillin-resistant *Staphylococcus aureus* (MRSA) with airborne transmission, both through the analysis of outbreaks (Farrington et al.

1990, Kumari et al. 1998) and through the sampling of air and surfaces in the environment (Noble 1962, Hathway et al. 2008). Many such studies indicate the role of general nursing activities such as bed-making (Roberts et al. 2006, Hathway et al. 2008) on the dispersion of the bacteria in the environment leading to environmental contamination and a increased risk of subsequent infection through indirect contact transmission. *Clostridium difficile* has also been associated with environmental dissemination and anecdotal suggestions of an airborne route have recently been supported by the sampling and culturing of *Clostridiumdifficile* spores from the air and high surfaces in a ward (Roberts et al. 2008). Of particular concern for hospitals, and of relevance to this paper, are those pathogens that are highly contagious and have a relatively short incubation period such that infected individuals are likely to spread the infection during the timescale that they are hospitalized. Several infections fall into this category including norovirus and influenza, which have the potential to rapidly infect whole wards, including the healthcare staff, resulting in ward closures, cancelled operations and pressure on the hospital operation (Chadwick et al. 2000). The incubation period for influenza is typically 1-3 days and patients may then be infectious for a period of 4-6 days (Hawker et al. 2001). Norovirus has a similar incubation period (1-2 days), but the patient is usually only highly infectious for around 2 days (Farr et al. 2004).

With mounting pressure on those who design and manage healthcare estates to meet both stringent infection and CO_2 reduction targets, there is a need for a better understanding of the interrelationships between airflow, infection, energy and comfort that can be applied to generic patient areas. This paper considers an approach to formally evaluating the trade-off between infection risk and energy performance through linking epidemic models with cost data. A stochastic formulation of a Susceptible-Exposed-Infector-Removed (SEIR) model coupled with the Wells-Riley equation is applied to a hypothetical hospital ward to explore the influence of environmental and disease parameters on the progression of an outbreak. A cost comparison is then made by evaluating the cost of treating infections against the costs of ventilating an environment. The study examines the level of uncertainty in the model and the data required to attain a reliable output.

AIRBORNE INFECTION OUTBREAK MODEL

Disease Dynamics

Models describing the dynamics of infectious diseases have been developed since the 1900's when scientists started to recognise patterns in the transmission of diseases that could be described mathematically. Today, general models for disease transmission are widely used and are well documented (Bailey 1957). A disease outbreak in a general population is commonly described by the process illustrated in Figure 1.

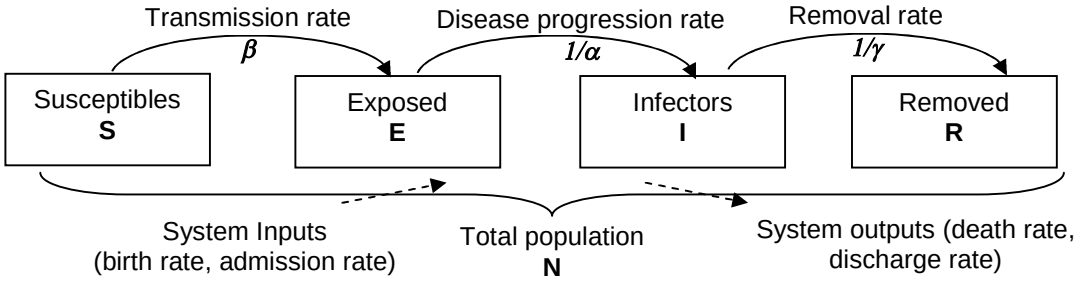


Figure 1: SEIR approach to evaluating a disease outbreak

Susceptible individuals (S) are exposed to infection at a particular rate (β) depending on the disease, transmission characteristics and prevalence within the population. Once exposed (E), individuals incubate the disease for a period of time (α) before becoming infectious themselves. As infectors (I) they potentially transmit the disease to others for a period of time (γ) before they are removed (R) from the process. The term removed is commonly used as a "catch-all" state that could include those who recover, those who may be physically removed by say isolation and those who die from the disease. If appropriate the process can be amended to separate out these different states. The total population involved in the process (N) comprises the sum of the Susceptible, Exposed, Infectors and Removed states at any point in the outbreak.

The basic process outlined in Figure 1 is known as an SEIR model and forms the underlying approach in this analysis. In its simplest deterministic form it is a series of differential equations that describe the rate of transition of people between the four states (Noakes et al. 2006). This can be appropriate for evaluating overarching behaviour and the role of different parameters as well as modelling disease transmission in large populations. However as the focus on this study is on a hospital ward, where the population is small and potentially transient it is essential to consider further the dynamics of transmission and the application of the SEIR model.

It is straightforward in an SEIR model to include the rates at which people enter or leave a population. In a population as a whole, this is most commonly the birth and death rates while in the context of a hospital outbreak this could be admission and discharge rates (Cooper et al. 1999). The model can also be extended to incorporate a range of other effects including the impact of vaccination and immunity (Chen and Liao 2008) and interaction between different diseases such as the impact of HIV/AIDS on tuberculosis dynamics (Massad et al. 1993). Dealing with different groups within a population is also possible although is more complex. Populations in hospital wards will comprise a range of people including patients, visitors, nursing staff, clinicians and ancillary staff, and the type of ward and management of the hospital will determine the time that each group spend on a ward and the frequency of visits. Cooper et al (1999) considered the dynamics of MRSA transmission on a ward and separated the population into separate staff and patient cohorts to incorporate the different interaction between them.

Several researchers including Fraser (2007) have developed models to simulate transmission within and between households to address the non homogeneous mixing seen in real populations; such an approach could also be applicable to mixing between groups in hospital wards.

In this case here we simplify the approach by considering that the population remains constant and not differentiating between groups of people. However we consider a stochastic formulation to include "chance" effects that are inherent in small populations. In this case we follow the approach used in Noakes and Sleigh (2009) and consider the outbreak as a series of events over time. In a small time interval, *dt*, such that the probability of more than one event is negligible, one of four outcomes is possible:

1. A new susceptible becomes exposed with probability Pr(SE) (S-1, E+1, I, R remain the same)
2. An exposed person becomes infectious with probability Pr(EI) (E-1, I+1, S,R remain the same)
3. An infector is removed with probability Pr(IR) (I-1, R+1, S, E remain the same)
4. Nothing happens (S,E,I,R remain the same)

In each case the probability of the event happening is governed by the rate parameters in Figure 1 and the current values of S,E,I and R to give

$$\Pr(SE) = \beta SI, \qquad \Pr(EI) = \frac{E}{\alpha}, \qquad \Pr(IR) = \frac{I}{\gamma} \tag{1}$$

Following Renshaw's (1991) approach as described in Noakes and Sleigh (2009) the model uses a computationally efficient method to consider the time to the next event. This is done by first calculating the total probability that an event (outcomes 1-3 above) may occur which is given by

$$\Sigma \Pr = \Pr(SE) + \Pr(EI) + \Pr(IR) \tag{2}$$

Each event probability can then be normalized to give

$$\Pr(se) = \frac{\Pr(SE)}{\Sigma \Pr}, \qquad \Pr(ei) = \frac{\Pr(EI)}{\Sigma \Pr}, \qquad \Pr(ir) = \frac{\Pr(IR)}{\Sigma \Pr} \tag{3}$$

The inter-event time, t can then be determined using

$$t = -\ln(Y) / \Sigma \Pr \tag{4}$$

Where Y is a uniformly distributed random number $0 \le Y \le 1$

The numerical simulation of the outbreak then follows the process:

- calculation of Pr(se), Pr(ei) and Pr(ir) at the current time-step
- generation of a first random number, $0 \le Y \le 1$ to find the inter-event time
- generation of a second random number $0 \le X \le 1$ to select the infection event with:
  Event 1 if $0 \le X \le \Pr(SE)$,
  Event 2 if $\Pr(SE) < X \le \left(\Pr(SE) + \Pr(EI)\right)$,
  Event 3 if $\Pr(SE) + \Pr(EI) < X \le \left(\Pr(SE) + \Pr(EI) + \Pr(IR)\right)$
  Event 4 if $\Pr(SE) + \Pr(EI) + \Pr(IR) < X \le 1$.
- Change in the values of S,E,I and R according to the infection event

The infection simulations were conducted using Excel and VBA (Microsoft) with a Monte-Carlo approach to enable each model to be run up to 500 times to establish the mean and variance in behaviour. As the inter-event times are different in every simulation due to the random number in the event time definition, the results were mapped onto a regular time scale at the end of each run to be able to compare data across more than one simulation.

Airborne transmission model

The risk of airborne transmission is incorporated through the widely used Wells-Riley model (Riley et al. 1978) which relates infection risk to the pulmonary ventilation rate of susceptible individuals, p (l/min or ft^3/min), the ventilation rate of a space, Q (l/min or ft^3/min) and the rate of infectious material produced by each infector known as the quanta generation rate, q (quanta/h). As shown in Noakes et al. (2006) the Wells-Riley model can be incorporated into the SEIR model through defining the transmission rate parameter β as

$$\beta = \frac{pq}{Q} \tag{5}$$

It is important to note that this model is not without its limitations and while more detailed discussion is given elsewhere (Noakes and Sleigh 2009, Sze To and Chao 2010) there are two points that should be acknowledged here. Firstly the risk model assumes a completely mixed airflow which is unlikely in the best ventilated rooms and even more unlikely across a whole hospital ward. Although not included here, this limitation can be relatively easily addressed by combining the model with multizone ventilation tools such as CONTAM or Computational Fluid Dynamics (CFD) models to assess the role of airflow patterns on the spatial distribution of infectious quanta (Noakes and Sleigh 2009, Qian et al. 2009). The model results also depend upon the value of quanta generation which is a difficult parameter to define as it essentially encompasses the concentration of infectious material, the virulence of the pathogen, the host susceptibility and the ability of the infector to produce an aerosolised pathogen. Values of quanta are generally derived from past outbreaks and rely on often incomplete knowledge of airflows and averaged infection rates to determine typical values. Values reported in the

literature for a number of infections are given in Table 1 and indicate the variability even within a particular disease.

Table 1: Quanta production rate for a range of infectious diseases (*LN = Log normal)

Disease	Case	Quanta/h	Reported by
Tuberculosis	Average patient	1.25	Nardell *et al* (1991)
Tuberculosis	Outbreak in office building	12.7	Nardell *et al* (1991)
Tuberculosis	Human to guinea pig transmission	0.3-44	Escombe et al (2007)
Multi-drug resistant Tuberculosis	Human to guinea pig transmission (highest infectors)	40,52,226	Escombe et al (2008)
Measles	Outbreak in a school	570	Rudnick and Milton(2003)
Influenza	School cases in Taiwan	66.91 (LN*)	Liao et al (2005)
Influenza	Aircraft outbreak	79-128	Rudnick and Milton(2003)
SARs	Taipei Hospital outbreak	28.77 (LN*)	Liao et al (2005)
Rhinovirus 16	Experimental data of Dick et al 1987	1-10	Rudnick and Milton(2003)

OUTBREAK MODEL BEHAVIOUR

The behaviour of the infection model was examined using a hypothetical case that is intended to be representative of a ward environment. The parameter ranges used in the model are given in Table 2. As the focus of the modelling here is on the level of control offered by ventilation, it is assumed that there is no physical isolation of infected cases and therefore people move from state I to state R in the SEIR model at a rate determined by the infectious period of the disease.

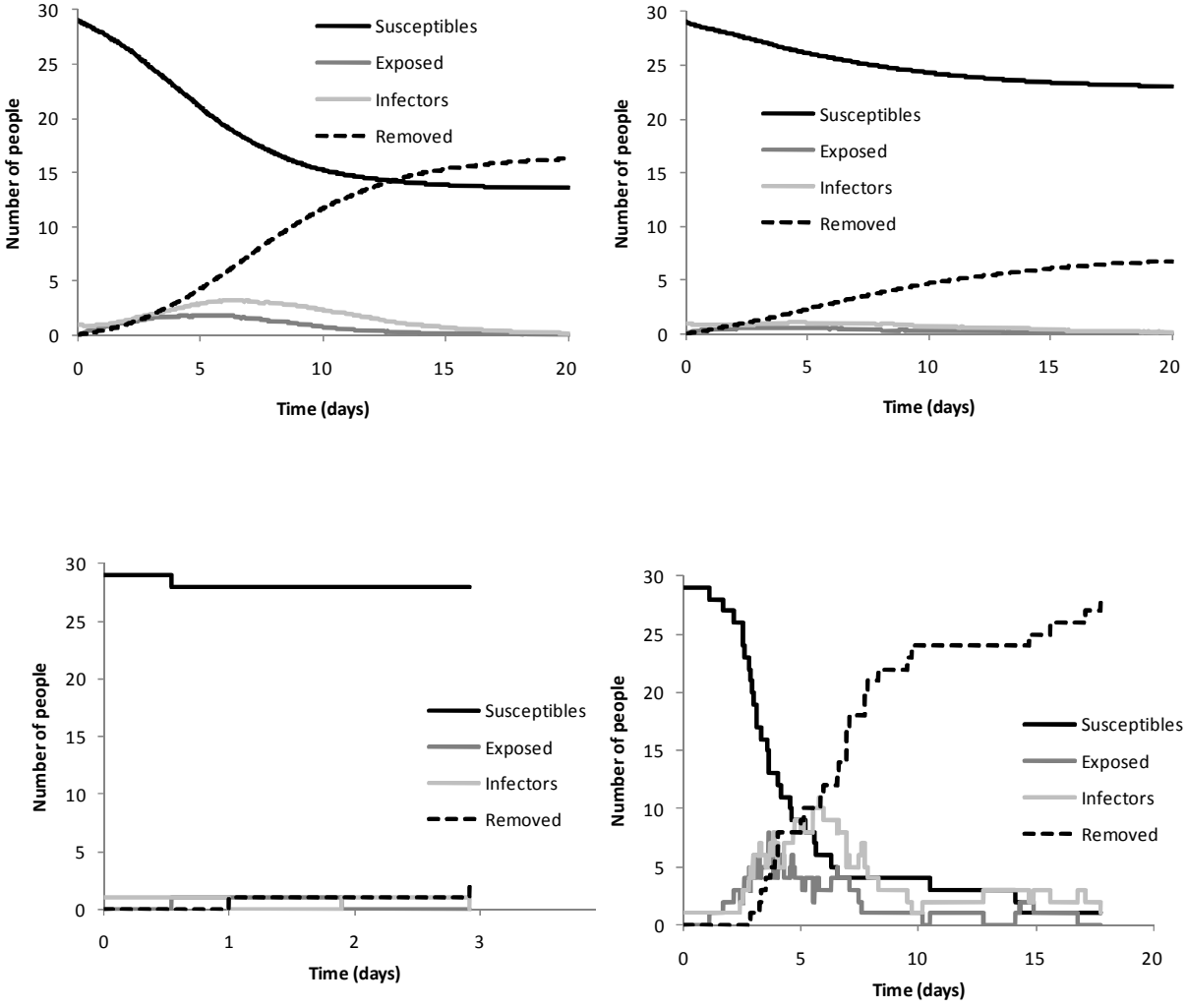
Table 2: Parameters used in the simulations.

Ward volume, V	1000 m^3 (35315 ft^3)	Pulmonary ventilation rate, p	10 l/min (0.35 ft^3/min)
Ventilation rate	3-12 AC/h	Quanta generation rate, q	5-20 quanta/h
Initial number of susceptibles, S	30	Disease incubation period, $1/\alpha$	1 day
Initial number of infectors, I	1	Disease infectious period, $1/\gamma$	1-2 days
Initial number of exposed, E	0	Duration of simulation	20 days
Initial number of removed, R	0		

Outbreak Dynamics

Figures 2 and 3 show typical simulation results, presenting average behaviour over 500 simulations and outbreak dynamics from a single run respectively. As expected, the mean results in Figure 2 show classic epidemic model behaviour that concur with previous deterministic approaches (Noakes and Sleigh 2006, Chen and Liao 2008) and suggest that an increase in ventilation rate may reduce both the total number of cases of an infection and the peak number of infectors. However the stochastic model enables the variability of the transmission process to be modelled, and as can be seen in Figure 3 the same set of conditions can lead to very different results. In Figure 3(a), the first infector (index case) only manages to

infect one other before both are removed. The infection therefore fails to spread and as such there is no outbreak. However in Figure 3(b) the infection has started to spread before cases are removed and a full blown outbreak occurs. As both scenarios have the same set of physical and disease parameters the difference between the two cases is due to the random nature of the stochastic model and the particular combination of parameters.



(a) Index case removed before infection spreads

(b) Infection spreads before removal leading to full outbreak.

Figure 3: Results from two single runs of the simulation with data as Table 2, q = 10 quanta/h, γ = 2 days and ventilation rate = 3 AC/h (a) Index case removed before infection spreads (b) Infection spreads before removal leading to full outbreak.

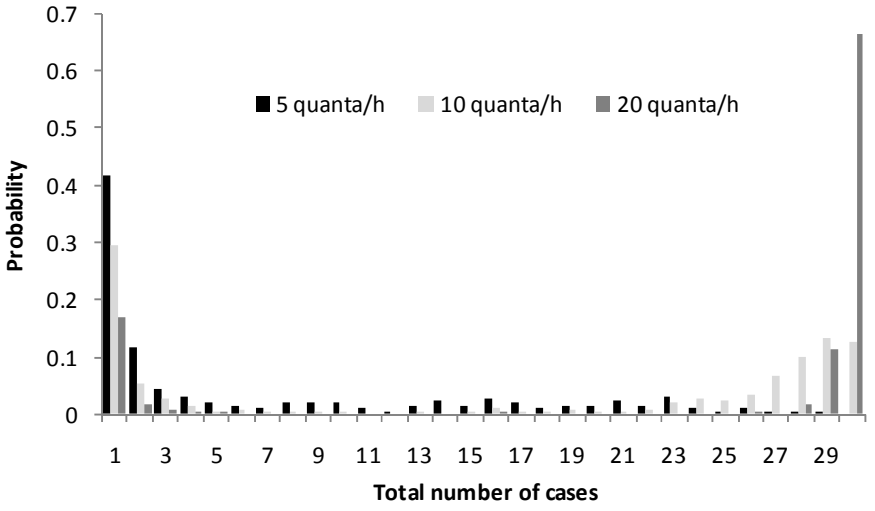
To further examine the variability in the model and the influence of disease and environmental parameters Figure 4 presents the probability distributions for the total number of cases over 500 simulation runs for both air change rates. A probability of only one case indicates that the infection has not spread beyond the index case, while 30 cases indicates that every person has succumbed to the infection. The results clearly show that as the transmission rate (β) increases, the distribution of the total size of the epidemic changes. As may be expected a lower value of β (lower quanta rate or higher ventilation rate) results in a distribution that is skewed to the left with the epidemic tending to die out before significant numbers are infected. However as β increases the results show a bimodal distribution with the likely outbreak size clustered at either end of the graph. Although the average behaviour of the model for such scenarios indicates that the number of cases will be in the middle of the range (Figure 2), the results in Figure 4 suggest that in most cases the behaviour is at the extremes; either the outbreak fails to get going with only a small number of cases or it progresses to a critical point whereby the majority of people are likely to be infected. This behaviour has been identified in mathematical texts examining the total size of stochastic epidemics and is related to the reproductive rate of the infection. In classic epidemic modelling theory the Reproduction Rate, Ro, of an outbreak is a measure of the average number of infections produced by a typical case and defined as

$$Ro = \frac{\beta}{\gamma} N \qquad (6)$$

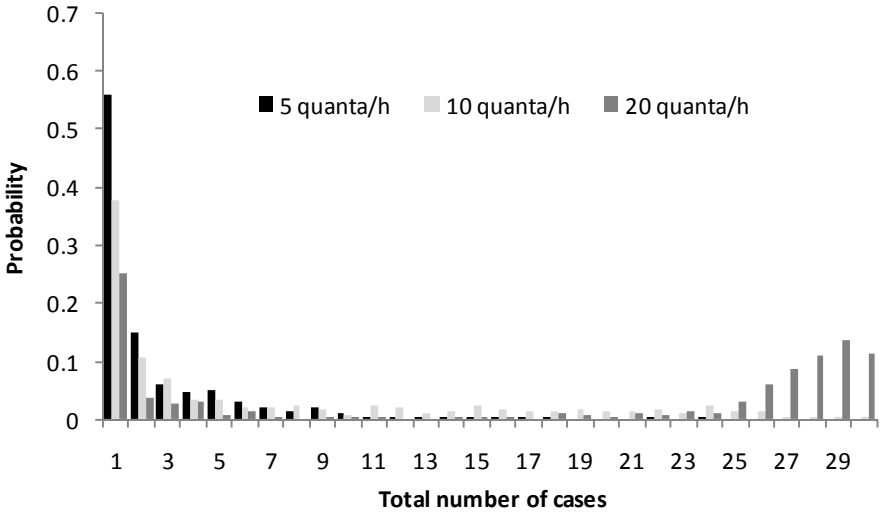
The parameter gives an indication of the likelyhood of an epidemic, and in a deterministic model Ro<1 indicates that the disease will die out, while Ro>1 is indicative of a full outbreak. Similar behaviour is seen in the probability distributions produced by stochastic models. Allen (2008) indicates that an outbreak with Ro less than or close to one will tend to die out early on, and the distribution for the number of cases will be skewed to the left. When Ro>1 the distribution becomes bimodal and increasingly skewed to the right as Ro increases. The values of Ro for the cases modelled in Figure 4 are given in Table 3 and can be seen to concur with the behaviour indicated in Allen (2008).

Table 3: Reproduction Rate (Ro) for conditions in Figure 4.

Ventilation rate (AC/h)	Quanta/h	β	Ro
3	5	1×10^{-3}	1.49
	10	2×10^{-3}	2.98
	20	4×10^{-3}	5.96
6	5	5×10^{-4}	0.74
	10	1×10^{-3}	1.49
	20	2×10^{-3}	2.98



(a) ventilation rate = 3 AC/h



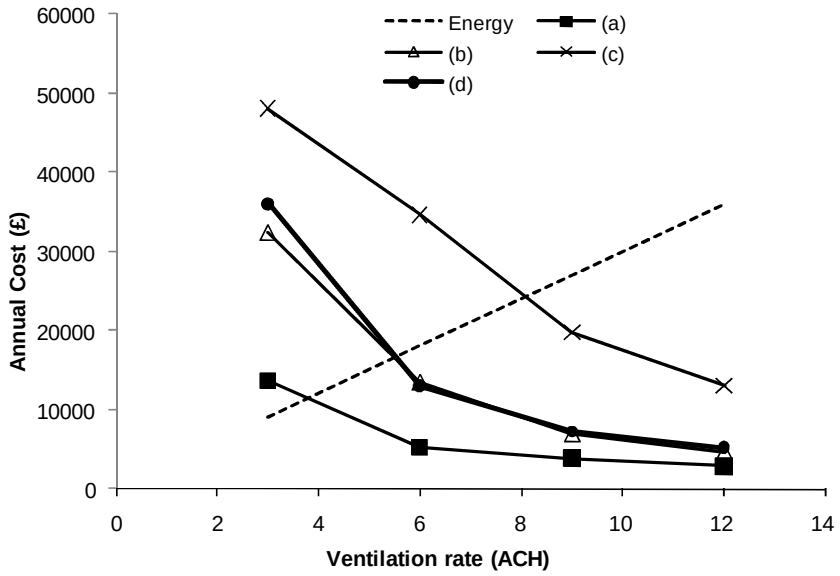
(b) ventilation rate = 6 AC/h

Figure 4: Probability of total number of cases for conditions in table 2, γ = 2 days and quanta production between 5 and 20 quanta/h

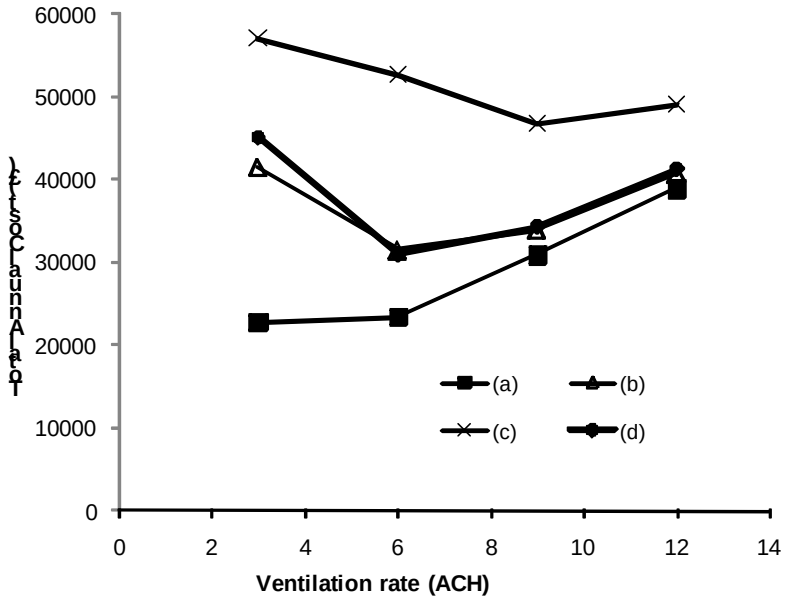
COST-BENEFIT ANALYSIS

While the results suggest that for some infections improved ventilation leading to greater dilution of airborne pathogens could potentially reduce the size and severity of an outbreak, it is not immediately clear whether investing to improve ventilation is really a viable approach for a hospital to take. To provide a means for formally assessing this, a simple financial appraisal method is explored by considering a cost for each air change provided and a cost to treat each case of an infection. By running the infection risk model for a range of disease and environmental parameters to determine the average total number of cases, it is straightforward

for a particular scenario to create a plot typical of Figure 5(a), showing the costs versus air change rate for both treatment of infections and energy consumption. For a particular disease scenario it is then possible to determine the optimum ventilation from the minimum total cost, as shown in Figure 5(b).



(a) Energy and treatment costs



(b) Total cost curves

Figure 5 Potential trade-off between energy and treatment costs for a hypothetical case considering costs associated with air movement only (a) q= 5 quanta/h, γ = 2 days (b) q= 10 quanta/h, γ = 2 days (c) q= 20 quanta/h, γ = 2 days (d) q= 20 quanta/h, γ = 1 day

In the case of Figure 5 it was assumed that in a hospital with 8 wards of 1000 m^3 (35315 ft^3) that there was one outbreak of an infection in a year that followed the average behaviour predicted by the infection risk model. The infection had an incubation period of 1 day, an infectious period of 1 or 2 days and a quanta generation rate per infector of 5 or 10 quanta /h. Each infection was assumed to cost the hospital £2000; this could be in treatment, lost bed days or staffing issues. The energy cost per air change rate for all 8 wards was assumed to be £3000 based on continuous operation of a mechanical system with a fan power of 2 W/l/s (56.6 $W/ft^3/s$) and a cost of electricity of 7.7p/kWh. The results clearly show that the trade-off between energy costs and infection will depend very strongly on the disease characteristics, with the optimum ventilation ranging from 3 AC/h for the lowest infectivity disease (case (a)), to 6AC/h for cases (b) and (d) and 9AC/h for case (c). As may be expected a higher quanta generation rate or a longer infectious period both increase the likely severity of an outbreak and hence the treatment cost for a hospital. In such cases the case for improved ventilation provision becomes stronger even to prevent only one outbreak per year.

Although in theory this approach is straightforward, there is a considerable challenge in practice in being able to incorporate both the variability in the risk of infection and to put realistic costs to both the treatment of the infection and the ventilation provision. The case considered in Figure 5 serves to demonstrate potential outcomes, but will be very dependent on the specifics of the disease and the various costs. Here the most appropriate level of ventilation appears to be between 3 and 9 air changes per hour, but this will change significantly depending on the cost of the infection. In addition the ventilation costs presented here only consider those that are associated with moving the air. While this would be reduced in a naturally ventilated hospital, regardless of the ventilation approach there is almost certainly a cost associated with heating and/or cooling and conditioning the air which will be very dependent on local climate, design of system and regulations. For example in the UK, heating is a certainty for at least six months of the year, cooling/conditioning will depend on application and location and recirculation of mechanically ventilated air is not permitted (Department of Health 2007) restricting energy saving to heat recovery devices which are again system dependant. In other climates, cooling and conditioning will be the primary concern with heating a negligible aspect. However, regardless of system design or location the need to modify the condition of the air will add to the cost, in many cases substantially and will rise with air change rate.

To evaluate this further, if it is assumed that that the hospital is in a region requiring heating but no cooling/conditioning and has a full fresh air system with 50% heat recovery the ventilation heat loss can be estimated through combining the ventilation conductance (CIBSE 2006) with the degree day approach using the equation.

$$\text{Annual heat loss (Wh)} = 0.5\frac{1}{3}NV24D_dE \qquad (6)$$

Here N is the ventilation rate (AC/h), V is the volume of the space (m^3), Dd are the number of degree days and E is the intermittancy factor. For the case in Figure 5 with 2100 degree days (typical for London region in the UK), E = 1 and an energy cost for heating of 4p/kWh (assumed to be gas and therefore lower than the electricity costs), this would increase the cost per air change rate from £3000 to £11064. As a consequence this would put the optimal ventilation rate at 3 air changes per hour or less and any increases will only be cost effective for the highest risk infections. While this is a simple theoretical example it is clear that the heating and/or cooling costs will almost certainly dominate in a real case, will vary substantially with system design and climate, and unless there is effective heat recovery in place will substaintially change the result. However despite this variation, putting a cost to the ventilation in a real case, while specific to a particular building and climate, is likely to be the easiest of the values to determine with modern Dynamic Thermal Modelling software tools and/or Building Energy Management system data. Other than fluctuations in weather conditions and energy costs the ventilation costs will remain broadly constant in a particular space regardless of infection, clinical process or operational procedures.

However putting costs to an infection presents a much greater challenge. In this case the costs will encompass both direct treatment costs, such as antibiotics, and the impact of the infection on the operation of the hospital. The later may include the costs of additional patient stay, the costs associated with staff shortages, the costs associated with cancellation of operations and procedures, the costs of additional cleaning and disinfection and even the need to accommodate patients in another ward or even another hospital. The actual costs here will depend on the actual infection concerned and the other pressures that the hospital is under at the time, and in reality may even change over time depending on the severity of an outbreak. For some infections the social and economic costs that result from the spread of an infection may also be a significant factor, as seen particularly in the SARs outbreak and to a lesser extent with the 2009 H1N1 influenza pandemic. In both cases the high mortality rate and/or high level of transmissibility make reducing the risk of transmission to the wider community a priority that should also be considered in cost calculations. Indeed in the UK it has been estimated that the preparation and response to the influenza pandemic totalled £1.2 billion (Hine 2010) for the vaccine and antiviral drug manufacture, extra face-masks and respirators and public health campaigns alone, without even including the cost of work absenteeism and other societal impacts. While in this case there is no evidence that higher levels of control in hospitals could have reduced the costs, it serves to emphasise the very high economic cost of major infectious disease outbreaks and the savings that can be made where containment is a viable option.

Even considering just the hospital aspects of an infectious disease outbreak, establishing costs will also depend on the method of calculation. In many cases this dominated by how a marginal bed-day is valued which is in part linked to a countries healthcare system (Graves et al 2010). Published data on costs is both limited and variable, however a number of authors give evaluations that are useful for establishing very rough appropriate costs. Plowman et al. (2001) considered 4000 patients admitted to a district general hospital in 1994-5 and estimated the

additional cost across all infections to be of the order of £3000 per patient. In a disease specific assessment, Ghantoji et al. (2010) reviewed published studies on C diff infections and from the limited data available indicated costs of $2871-$4846 (approx. £2000-£3300) per primary case within the USA and $5243-$8570 (approx. £3500-£5800) outside. Zingg et al. (2005) estimated the cost of a norovirus outbreak among 16 patients and 29 healthcare workers to be $40675 (approx. £27500) which equates to a per patient cost of approx. £1700. Based on these very approximate estimates Figure 6 indicates the effect that changing both the cost of infection and the cost of energy may have on the total cost and hence the optimum ventilation for case (b) in Figure 5. The results indicate that changing either cost has a dramatic effect on the overall outbreak cost and supports the need for good economic data if such a model is used for assessment.

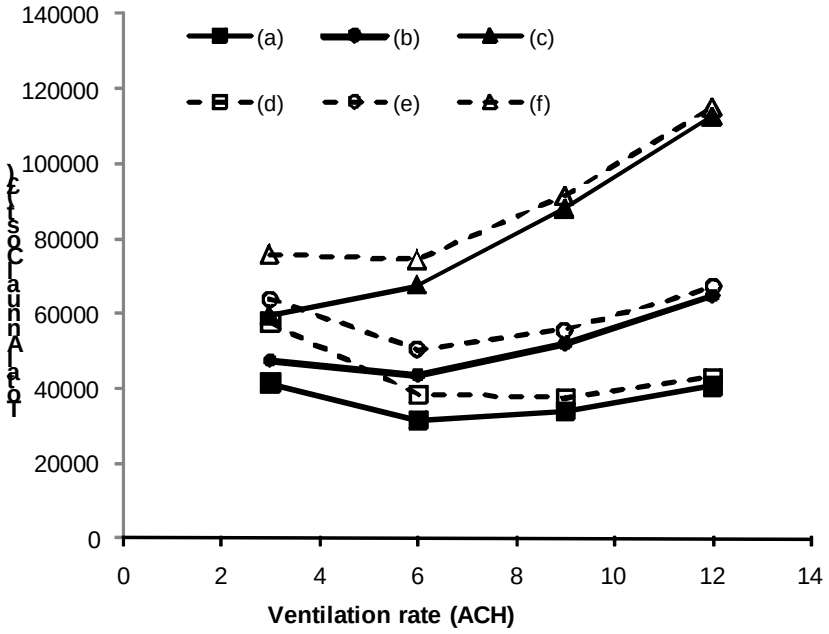


Figure 6: Influence of infection and energy costs on the outcome of the model for case (b) in Figure 5, q = 10 quanta/h, γ = 2 days. (a) energy £3000 per AC/h, infection £2000 per case (b) energy £5000 per AC/h, infection £2000 per case (c) energy £9000 per AC/h, infection £2000 per case (d) energy £3000 per AC/h, infection £3000 per case (e) energy £5000 per AC/h, infection £3000 per case (f) energy £9000 per AC/h, infection £3000 per case

A further consideration is the stochastic variance in the likely dynamics of an infection as demonstrated in Figure 4. Figure 7 takes this into account by plotting the total cost (energy + treatment cost) against probability for four different air change rates. Here the disease parameters are again q = 10 quanta/h and γ = 2 days and the energy and treatment costs are assumed to be £9000 per AC/h and £3000 per case respectively. At the lowest air change rate, the base cost associated with energy only is minimised, however such low dilution is ineffective

against airborne transmission and results indicate that there is around a70% chance that the cost will be approximately five times greater. Increasing the ventilation rate to 3 AC/h increases the base energy cost, but substantially reduces the risk of a high cost outbreak to approximately 13%. A further increase to 6AC/h shows that the ventilation is now effective at reducing the epidemic however increasing the air change rate to 12 AC/h is clearly not cost effective for this particular infection scenario although it is the only case where the value of Ro is reduced below one.

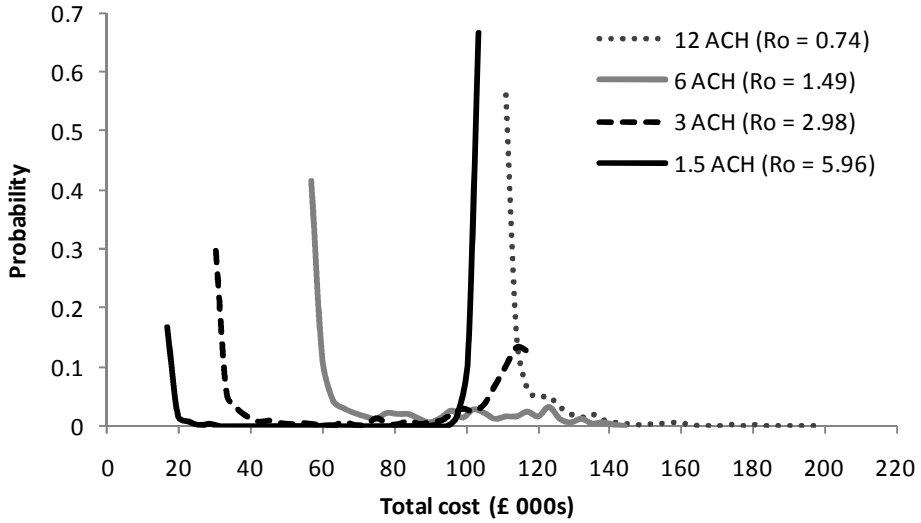


Figure 7 Probability of annual cost of an infectious disease outbreak assuming q = 10 quanta/h, γ = 2 days, energy cost £9000 per AC/h, treatment cost £3000 per case

Comparing Figures 6 and 7 suggests that using the optimum ventilation rate derived from a mean infection rate is a reasonable approach for design. While it doesn't capture the variance that will be present in reality, a hospital could regard the mean as the trend that they are likely to see over a period of a number of years. Although increasing the ventilation rate will not guarantee a reduction in infections it will reduce the probability of an outbreak occurring. However it is likely that in some cases when an outbreak does occur the severity will be the same regardless of the ventilation rate. As a result the cost and operational impact of a single large outbreak may remain the same despite changes to the ventilation, but the frequency with which a hospital is likely to experience a large outbreak could well be reduced.

DISCUSSION

The models presented here offer some insights into the risk of airborne related outbreaks in hospital environments. While the models as they stand could not be considered as robust or validated, they do provide a greater understanding as to the factors that influence the transmission of infection and therefore the criteria for designing ventilation in hospital wards. Perhaps the most valuable insights are around the level of uncertainty that is involved in predicting disease outbreaks in small populations and the need for case specific data to be able

to validate and subsequently use such models. The cases presented here, although based on appropriate parameters for infectious diseases in hospitals, deliberately do not attempt to simulate an actual infection as the level of uncertainty in the model parameters are such that there is a danger of the results being misinterpreted. Although limitations in the ventilation parameters are starting to be addressed (Noakes and Sleigh 2009, Qian et al. 2009), disease parameters present a greater difficulty. The infectious and incubation periods for most diseases are variable and although the range can be estimated with reasonable certainty fixed rate constants cannot deal with the change in infectiousness as a disease progresses or the increasing likelihood that a person will leave the state with time (Wearing et al. 2005). The value of quanta is perhaps the greatest unknown and as discussed with Table 1, is both variable and difficult to establish for the majority of diseases. As infections relevant to hospital outbreaks are likely to be transmitted by a combination of airborne, droplet and contact routes, determining the value of quanta is even more of a challenge. Researchers are looking to address some of these issues through developing disease transmission models based on a dose-response approach (Chen et al. 2009), and it is clear that further research in this area is essential to improve the robustness of risk models for hospital environments.

Dealing with the complexities of the population and the management of the hospital should also be considered for a real case. While the static population of 30 patients simulated here using a stochastic approach may be representative for certain hospital environments, in others it is too simplistic and it will be necessary to consider the interaction between different groups and the impact that this may have on the risk of transmission (Fraser 2007, Cooper et al 1999). This is particularly of concern where transmission of infection may occur prior to symptoms appearing, which is shown by Fraser et al (2004) to make control of an outbreak much more difficult. While using ventilation as a control strategy may offer greater protection in such cases compared to reliance on identification and isolation of infected cases alone, environments where there is movement of patients or staff between wards may still allow undetected transmission between spaces. The models presented here only consider the role of ventilation and in some senses are therefore a worst case scenario. In reality combining ventilation or other airborne controls with good surveillance and prompt treatment or isolation may enable an outbreak to be brought under control more easily than the models presented here suggest.

It is also worth commenting on the challenge of validating such models by comparing to real outbreak data. In many cases this is particularly difficult, as data records dates of cases rather than when individuals were actually infected and there are often several cases in an outbreak before it is identified as such and therefore the early cases are often missing (Fraser 2007). The issue is further compounded as changes in infection control procedure in response to the outbreak will probably change the dynamics of transmission and therefore alter modelling assumptions. Fraser (2007) describes an approach for developing reproduction numbers at an individual level which take account of the fact that the contact rate parameter □ may change during the course of an outbreak and indicates that this offers a potential solution to dealing with incomplete infection data during a real outbreak.

Despite these difficulties, the models presented here set out an approach for evaluating the ventilation design parameters from a cost-benefit perspective and as such offer a potential framework for assessment. While there are challenges in appropriately simplifying the transmission scenario and determining suitable costs for both ventilation provision and the consequences of infection, the ability to consider the ventilation from a quantitative risk perspective at the design stage offers a rational for selecting appropriate ventilation that is beyond the comfort and energy requirements of a space. For example, the results presented here for short incubation period infections with a quanta generation rate under 20 quanta/h, support the case for good ventilation in the region of 3-8 AC/h depending on the actual infection, local climate and ventilation system, but do not show significant further benefit beyond this range for any of the costs considered. Even this level of knowledge at the design stage, combined with a view on patient cohort and the likelihood of a ward to experience outbreaks could help ensure that ventilation is not over or under specified. In addition, the models have the potential to help understand the likely extent and financial impact of an outbreak in an existing ward benefiting those planning mitigation strategies.

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REFERENCES

Allen LJS. 2008. An introduction to stochastic epidemic models. In: Brauer F et al (Ed) *Mathematical Epidemiology* Springer-Verlag, Berlin Heidelberg; Chapter 3; 81-132

Bailey NT. 1957. *The Mathematical Theory of Epidemics*. London: Griffin & Co.

Booth W, Beato B, Noakes C, Fletcher L, Sleigh A, Tomlinson N .2009. Characterisation of the protection provided by the ventilation strategy in hospital isolation rooms *Healthy Buildings 2009, Syracuse 13-17th September*

Chadwick PR, Beards G, Brown D et al. 2000. Management of hospital outbreaks of gastro-enteritis due to small round structured viruses. *Journal of Hospital Infection* 45:1-10

Chen SC, Chio CP, Jou LJ, Liao CM. 2009. Viral kinetics and exhaled droplet size affect indoor transmission dynamics of influenza infection. *Indoor Air*

Chen SC, Liao CM. 2008. Modelling control measures to reduce the impact of pandemic influenza among schoolchildren. *Epidemiology and Infection* 136: 1035-1045

Chow TT, Yang XY .2004. Ventilation performance in operating theatres against airborne infection : review of research activities and practical guidance. *Journal of Hospital Infection* 56: 85-92

CIBSE. 2006. Guide A: Environmental Design. 7th Edition

Cooper BS, Medley GF, Scott GM. 1999. Preliminary analysis of the transmission dynamics of nosocomial infections: stochastic and management effects. *Journal of Hospital Infection* 43: 131 – 147

Department of Health. 2007. Health Technical Memorandum HTM 03-01: Specialised ventilation for healthcare premises, Part A: Design and Validation. The Stationary Office, London

Escombe AR, Oeser C, Gilman RH et al .2007. The Detection of Airborne Transmission of Tuberculosis from HIV-Infected Patients, Using an In Vivo Air Sampling Model. *Clinical Infectious Diseases*, 44;1349–1357.

Escombe AR, Moore DAJ, Gilman RH et al .2008. The Infectiousness of Tuberculosis Patients Coinfected with HIV, *PLOS Medicine* 5; 1387-1397

Farr BM. 2004. Nosocomial Gastrointestinal Tract Infections. In: Mayhall CG, (Ed) *Hospital Epidemiology and Infection Control*, 3rd edn. Lippincott-Williams & Wilkins, London, UK; Chapter 24; 351-383

Farrington M, Ling J, Ling T and French GL. 1990. Outbreaks of infection with methicillin-resistant *Staphylococcus aureus* on neonatal and burns units of a new hospital. *Epidemiology and Infection* 105: 215 – 228

Fraser C. 2007. Estimating individual and household reproduction numbers in an emerging epidemic, *PLoS one* 2: e758

Fraser C, Riley S, Anderson RM, Ferguson NM. 2004. Factors that make an infectious disease outbreak controllable. *Proceedings of National Academy of Sciences USA*. 101: 6146-51.

Friberg B, Lindgren M, Karisson C, Bergstrom A, Friberg S .2002. Mobile zoned/exponetial LAF screen: a new concept in ultra-clean air technology for additional operating theatre ventilation. *Journal of Hospital Infection* 50: 286-292

Ghantoji SS, Sali K, Lairson DR, DuPont HL, Garey KW. 2010. Economic healthcare costs of Clostridium difficile infection: a systematic review *Journal of Hospital Infection* 74, 309e318

Graves N, Harbarth S, Beyersmann J, Barnett A, Halton K, Cooper B. 2010. Estimating the Cost of Health Care–Associated Infections: Mind Your p's and q's *Clinical Infectious Diseases* 50:1017–1021

Hathway EA, Fletcher LA, Noakes CJ, Sleigh PA, Elliot M, Clifton I. 2008. Bioaerosol Production from Routine Activities within a Hospital Ward In: *Indoor Air 2008, Copenhagen 17-22nd August*

Hawker J, Begg N, Blair I, Reintjes R, Weinberg J. 2001. Communicable disease control handbook, Blackwell Science, UK 124-126

Hine D. 2010. The 2009 Influenza Pandemic: An independent review of the UK response to the 2009 influenza pandemic. The UK Cabinet Office

Jensen, PA, Lambert LA, Iademarco MF, Ridzon R .2005. Guidelines for Preventing the Transmission of *Mycobacterium tuberculosis* in Health-Care Settings. *MMWR*, 54: RR-17

Kumari DNP, Haji TC, Keer V, Hawkey PM, Duncanson V, Flower E. 1998. Ventilation grilles as a potential source of methicillin-resistant *Staphylococcus aureus* causing an outbreak in an orthopaedic ward at a district general hospital. *Journal of Hospital Infection* 39: 127-133

Liao CM, Chang CF, Liang HM .2005. A Probabilistic Transmission Dynamic Model to Assess Indoor Airborne Infection Risks *Risk Analysis,* 2: 1097-1107

Massad E, Burattini MN, Coutinho FAB, Yang HM, Raimundo SM. 1993. Modelling the interaction between AIDS and tuberculosis. *Mathematical and Computational Modelling* 17; 7-21

Nardell EA, Keegan J, Cheney SA, Etkind SC. 1991. Airborne infection: Theoretical limits of protection achievable by building ventilation. *American Review of Respiratory Disease* 144: 302 – 306

Noakes CJ, Beggs CB, Sleigh, PA, Kerr KG. 2006. Modelling the Transmission of Airborne Infections in Enclosed Spaces. *Epidemiology and Infection* 134; 1082-1091

Noakes CJ, Sleigh PA .2009. Mathematical models for assessing the role of airflow on the risk of airborne infection in hospital wards. *Journal of the Royal Society Interface*. 6, S791-S800

Noble, W. C. 1962. Dispersal of Staphylococci in Hospital Wards. *Journal of Clinical Pathology,* **15**(6)**,** 552-558.

Plowman R, Graves N, Griffin MAS, Roberts JA, Swan AV, Cookson B, Taylor L. 2001. The rate and cost of hospital-acquired infections occurring in patients admitted to selected specialties of a district general hospital in England and the national burden imposed *Journal of Hospital Infection* 47: 198–209

Qian H, Li YG, Nielsen PV, Huang, XH. 2009. Spatial distribution of infection risk of SARS transmission in a hospital ward *Building and Environment* 44:1651-1658

Renshaw E. 1991. *Modelling Biological Populations in Space and Time*. Ed. Cannings C, Hoppensteadt FC, Segel LA. Cambridge University Press.

Riley EC, Murphy G, Riley RL. 1978. Airborne spread of measles in a suburban elementary school. *American Journal of Epidemiology*. 107: 421 – 432

Roberts K, Hathway A, Fletcher LA, Beggs CB, Elliott MW, Sleigh PA. 2006. Bioaerosol production on a respiratory ward. *Indoor and Built Environment*. 15: 35-40

Roberts K, Smith CF, Snelling AM, Kerr KG, Banfield KR, Sleigh PA, Beggs CB. 2008. Aerial dissemination of Clostridium difficile spores, *BMC infectious diseases*

Rudnick SN, Milton DK. 2003. Risk of airborne infection transmission estimated from carbon dioxide concentration. *Indoor Air* 13; 237-245

Sze To GN, Chao CYH .2010. Review and comparison between the Wells-Riley and dose-response approaches to risk assessment of infectious respiratory diseases. *Indoor Air*. 20: 2-16

Wearing HJ, Rohani P, Keeling MJ .2005. Appropriate models for the management of infectious diseases. *PloS Medicine* 2: e174

Zingg W, Colombo C, Jucker T, Bossart W, Ruef C .2005. Impact of an outbreak of norovirus infection on hospital resources. *Infection control and hospital epidemiology*, 26: 263-267

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Mathematical models for assessing the role of airflow on the risk of airborne infection in hospital wards

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Understanding the risk of airborne transmission can provide important information for designing safe healthcare environments with an appropriate level of environmental control for mitigating risks. The most common approach for assessing risk is to use the Wells–Riley equation to relate infectious cases to human and environmental parameters. While it is a simple model that can yield valuable information, the model used as in its original presentation has a number of limitations. This paper reviews recent developments addressing some of the limitations including coupling with epidemic models to evaluate the wider impact of control measures on disease progression, linking with zonal ventilation or computational fluid dynamics simulations to deal with imperfect mixing in real environments and recent work on dose–response modelling to simulate the interaction between pathogens and the host. A stochastic version of the Wells–Riley model is presented that allows consideration of the effects of small populations relevant in healthcare settings and it is demonstrated how this can be linked to a simple zonal ventilation model to simulate the influence of proximity to an infector. The results show how neglecting the stochastic effects present in a real situation could underestimate the risk by 15 per cent or more and that the number and rate of new infections between connected spaces is strongly dependent on the airflow. Results also indicate the potential danger of using fully mixed models for future risk assessments, with quanta values derived from such cases less than half the actual source value.

Keywords: airborne infection; ventilation; Wells–Riley; stochastic; hospital

1. INTRODUCTION

Airborne transmission of infectious diseases is a subject of increasing interest driven by a wide range of factors including: greater understanding of the role played by indoor air and ventilation provision in the dispersal and transport mechanisms of a wide range of pathogens; changing expectations of hospital patients, particularly in developed countries; and the emergence of new or drug-resistant disease strains with the potential to spread on a global scale. Tuberculosis (TB) is an archetypal example of a disease that is transmitted by a true airborne route; primary infection occurs when droplet nuclei containing *Mycobacterium tuberculosis* bacilli are inhaled. These tiny particles (typically $<5\,\mu m$ in diameter) can remain suspended in the air for long periods of time with local airflow pathways inside a building determining their fate. TB is a particular concern as it is once again a worldwide health problem, compounded by the increased susceptibility to *M. tuberculosis* in HIV/AIDS patients, ease of world travel and the increased prevalence of multidrug-resistant tuberculosis (MDR-TB). Specialist ventilation and isolation facilities are recommended to control nosocomial (hospital) spread (Siegel *et al.* 2007) and those on the front line advocate secondary environmental control measures such as ultraviolet germicidal irradiation to further minimize risk (Nardell *et al.* 1991; Escombe *et al.* 2009). Although excluded from the medical definition of airborne infection, the transmission of disease by pathogen-contaminated droplets also involves transport through the air. The emergence of severe acute respiratory syndrome (SARS) in 2002–2003 caused a global health scare (Riley *et al.* 2003), with the causative agent, a highly infectious coronavirus (Lipsitch *et al.* 2003), thought to be primarily spread through localized contact with contaminated droplets. However, there is evidence that individuals were apparently infected without sufficiently close contact with a known case (Scales *et al.* 2003), and retrospective studies of building airflow patterns suggested that airborne dispersal may play a significant role (Li *et al.* 2005). In recent months, the potential for a global influenza pandemic has created similar anxieties for those tasked with controlling wide-scale disease spread. Again the infection is linked to droplet transmission and the time scale for production of a vaccine and limitations of drug treatment mean that

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physical and procedural control strategies are the primary defence against widespread transmission (Morse *et al.* 2006).

Although many nosocomial infections are primarily associated with direct person-to-person contact, there is considerable evidence that aerial dissemination of pathogens may play an important role in many hospital-acquired infections. In recent years airborne transmission has been implicated in nosocomial outbreaks of *Staphylococcus aureus* (Farrington *et al.* 1990; Mertens 1996) and *Acinetobacter* spp. (Allen & Green 1987; Kumari *et al.* 1998) as well as many viral outbreaks. The high secondary attack rates seen in norovirus outbreaks have also been attributed to the dispersion droplets, released when patients vomit, that rapidly evaporate to form airborne droplet nuclei and are distributed by air currents around hospitals. With hospital design and operation in the developed world now driven by infection control targets and increasingly the energy use agenda, better understanding of the relationships between the design of the physical environment and the risk of infection is becoming increasingly essential in establishing robust guidance for those charged with developing and managing healthcare facilities. This paper reviews the application of the Wells–Riley model for relating the risk of airborne infection to parameters in the indoor environment and the developments applied to address some of the limitations in the original model. A stochastic formulation is presented which is coupled with a simple zonal ventilation model to demonstrate the role of airflow and population size on the risk of infection and the implications for design, risk assessment and future research.

2. MODELLING AIRBORNE INFECTION

Transmission of infection is a complex process at the best of times with the risk of disease determined by numerous factors that have considerable and uncertain variability including: the characteristics of the pathogen concerned, the infectiousness of the host, the media in which it is passed from source to new host and the immune response of the new host. Transmission through airborne routes complicates this further by adding the influence of building airflows to the process. Despite this, researchers in epidemiology have developed a range of approaches for modelling disease dynamics from the classic models such as Susceptible-Infector-Susceptible (SIS) and Susceptible-Infector-Removed (SIR) models, which make use of average rate coefficients to describe progression of a disease in a population (Bailey 1957) to more recent studies based on dose–response data (Jones *et al.* 2009) or that incorporate the pathogen–host biological interaction (Chen *et al.* 2009). Much of the previous research quantifying airborne infection rates in confined spaces has stemmed from the work of Wells (1955) and Riley *et al.* (1978), using the analytical expression known as the Wells–Riley equation. This relates the number of infective (I) and susceptible (S) people in a space, the room ventilation rate (Q, $\mathrm{m^3\,s^{-1}}$) and the quantity of infectious material in the air to predict the number of new cases infected, N_C, over a period of time t (s):

$$N_\mathrm{C} = S\left(1 - \mathrm{e}^{-Iqpt/Q}\right). \tag{2.1}$$

Here p ($\mathrm{m^3\,s^{-1}}$) is the pulmonary ventilation rate of susceptible individuals, while q represents a unit of infection termed as 'quantum', introduced by Wells (1955), to express the response of susceptible individuals to inhaling infectious droplet nuclei. He postulated that not all inhaled droplet nuclei will result in infection and defined a quantum of infection as the number of infectious droplet nuclei required to infect $1 - 1/\mathrm{e}$ susceptible people. The term quantum or quanta of infection is widely used in evaluating airborne infections and is usually interpreted as a measure that effectively indicates both the quantity and virulence of infectious material present in the air.

Numerous researchers have carried out risk-analysis studies based on this model including the evaluation of personal protective equipment (Gammaitoni & Nucci 1997), tuberculosis risk in buildings (Nardell *et al.* 1991) and the dispersion of *Bacillus anthracis* from envelopes (Fennelly *et al.* 2004). The study conducted by Gammaitoni & Nucci (1997) also showed a fundamental formulation of the Wells–Riley equation that enables transient ventilation effects to be included. An earlier study reviewing Wells–Riley type models (Beggs *et al.* 2003) highlighted that although the models give useful indications of expected transmission in a wide range of circumstances, their simple nature results in several limitations described here.

2.1. Disease dynamics

The original Wells–Riley formulation is confined to only predicting new cases of a disease, an assumption that is valid where the incubation period (or time for a new case to become infective) is longer than the time scale of the model. With the model most commonly used to evaluate TB transmission, this is generally justified as the incubation is typically weeks or even years, and (with the exception of long-term confinement such as prisons), occupants are generally not in contact longer than the incubation period. The assumption is also valid for short incubation period diseases if the model is applied over very short time scales, such as transmission of influenza on an aircraft as considered by Rudnick & Milton (2003). However, in the case of transmission of diseases such as influenza, SARS or norovirus in hospitals, which may have an airborne component to the transmission, the time scale of contact is comparable to the incubation period and therefore the dynamics of the disease must be considered. It is straightforward to extend the model to include the long-term dynamics of an infection by coupling with classic epidemic models as described in Noakes *et al.* (2006*a*). Such an approach enables both the disease and environmental parameters to be explored, allowing the combined role of nursing behaviour with controls such as ventilation, personal protective equipment or vaccination (Chen & Liao 2008) to be assessed through a single model. Interestingly, the original paper first describing the Wells–Riley

equation (Riley *et al.* 1978) applied it to a measles outbreak in a school, a disease and setting that do not meet the above criteria. To accommodate this the authors applied the model over discrete time periods, using the cases and susceptibles at the end of each period as the initial conditions for the next period rather than coupling with an epidemic model.

2.2. Population size

One of the key limitations with the Wells–Riley model concerns the small size of populations in hospital environments and the role that chance effects play in determining infection risk. Equation (2.1) is based on the Poisson law of small chances, which assumes that in a small enough time period only one new infection is likely. This is suitable for most airborne infections where it is easy to define a time period that approximates to this criterion. However, although the Wells–Riley model is derived from this probabilistic approach, it is more commonly used in deterministic simulations, with equation (2.1) used to predict average infection risk in different scenarios. In particular, the model has been used successfully in studies to examine both the impact of interventions on the progression of an infection, as well as retrospectively to find the average quanta production rate from outbreak data, particularly relating to TB transmission. Treating the model as one describing a deterministic process is only strictly suitable for large populations, and to understand the variability in risk for small numbers, such as hospital patients, it is necessary to apply the model in a stochastic simulation.

2.3. Proximity

The Wells–Riley model assumes that the air is well mixed leading to a uniform concentration of bioaerosols throughout the space. This is rarely true even in spaces with the best designed ventilation systems and therefore does not account for the influence of proximity between infective and susceptible people. In particular this is an issue when analysing the risk of infection in a space consisting of connected rooms, such as hospital wards. This can be partially addressed by using zonal ventilation or computational fluid dynamics (CFD) modelling techniques to simulate the airflow and dispersion of contaminants, revealing regions of good and poor mixing and areas of high contaminant concentrations that would constitute a higher risk to occupants. Zonal or network ventilation models are well used in evaluating ventilation flows in large multi-connected spaces such as whole buildings. While they are limited in that they are not capable of resolving local details of airflows and are less well suited to large spaces such as atria (Mora *et al.* 2003), they have been shown to give good prediction of bulk air movement and contaminant transport in a range of applications including natural ventilation (Asfour & Gadi 2007) and particle dispersion (Hu *et al.* 2007). Two of the most widely used models, COMIS and CONTAM, were developed by national laboratories in the USA and are used in both research and design applications (Chen 2009). Zonal modelling has previously been applied to airborne infection risk, including simulation of ultraviolet disinfection (Noakes *et al.* 2004*a*) showing good comparison to CFD models and studies by Ko *et al.* (2004) and Jones *et al.* (2009) considering TB transmission on an airliner. Ko *et al.*'s study used both a fully mixed model as well as approximating the spatial variation by dividing the airliner cabin into four zones with incomplete mixing between zones. Combining this with the Wells–Riley model and spatial distribution data from a real outbreak enabled them to show that compartmentalization of airflow in cabins acts to limit transmission of any infection throughout the entire aircraft. Jones *et al.* (2009) also adopted a zonal approach, dividing the aircraft into 34 zones with the ventilation and interzonal flows based on measured data with results indicating spatial transmission patterns dependent on the turbulent mixing between zones. CFD offers a strategy for modelling the detailed spatial distribution of pathogens in indoor environments. A number of recent studies have considered hospital applications (Chow & Yang 2004; Noakes *et al.* 2006*b*) or bioaerosol dispersal (Noakes *et al.* 2004*b*), and the 2003 SARS outbreak generated a lot of interest using CFD to model the spread of contagion within and between buildings (Yu *et al.* 2004; Li *et al.* 2005). A recent paper (Qian *et al.* 2009) has linked CFD simulations and the Wells–Riley model with results showing correlation between predicted and observed spatial infection risk. Despite the details available from CFD modelling, using the technique to simulate airflow in large multi-connected buildings requires significant computational resources that are unavailable or inappropriate in many cases. A recent review by Chen (2009) highlights a move towards the use of 'coarse grid' CFD and coupling CFD models to zonal ventilation models to provide higher levels of accuracy without excessive computational effort.

2.4. Infectious dose

Perhaps the biggest limitation with the Wells–Riley model is the representation of the infectious dose through the expression 'quantum' of infection. While this is a simple approach that is easily analogous to the concentration of a pathogen in the air, the single parameter cannot fully capture the complex interaction between infectors, pathogens and potential hosts that occurs in reality. As highlighted in Pujol *et al.* (2009), the Wells–Riley model is only appropriate for infections that can be modelled with an exponential dose–response where a single large dose can be considered to be the same as the equivalent in smaller doses over a longer time period. As such the model cannot incorporate the immune system response that may act to control pathogens arriving at low doses over a long time period and is likely to be inappropriate for estimating risk at low doses (Haas 1983). Nicas & Hubbard (2002) also recognize this limitation and go on to suggest that the Wells–Riley model is only strictly valid where infection is initiated by a single microorganism and the quanta represents the risk of this being inhaled and initiating infection. The model has

been most widely applied to TB, which is believed to satisfy these criteria (Escombe *et al.* 2007); however, it may be less appropriate for many other infections, especially where the infectious dose is low (Nicas & Hubbard 2002). Recent research is starting to develop strategies to address these weaknesses through the application of disease-specific characteristics and dose–response data, much of which has developed through risk assessment of pathogens in water and wastewater (Haas 1983; Mara *et al.* 2007). Studies focusing on airborne transmission include Armstrong & Haas (2007*a*,*b*) who outline a framework for using quantitative microbial risk assessment (QMRA) in modelling the risk of legionnaire's disease, using dose–response data from animal studies. Bartrand *et al.* (2008) consider a similar approach in the transmission of *B. anthracis*, again through fitting distribution models to published non-human dose–response data, while Jones *et al.*'s (2009) study also uses a QMRA approach in evaluating *M. tuberculosis* transmission. Chen *et al.* (2009) adopt a slightly different approach, using a Wells–Riley framework to describe global parameters, but linking both viral kinetics and the characteristics of exhaled bioaerosols to incorporate the disease characteristics in the transmission of influenza. The most recent studies in this area (Huang & Haas 2009; Pujol *et al.* 2009) are building on these dose–response model developments to consider the risk over time from single or multiple doses, enabling the immune response seen in reality to be incorporated into analyses. Although the primary interest in this paper is on the environmental parameters rather than the disease characteristics, these recent developments clearly offer a valuable strategy for understanding the role of pathogen–human interaction in disease transmission and are likely to play a key role in future model developments.

3. STOCHASTIC ZONAL MODEL

By considering equation (2.1) an infection rate λ can be written as

$$\lambda = \frac{Iqp}{Q}. \tag{3.1}$$

A stochastic formulation of the Wells–Riley equation is based on the probability that there are S uninfected susceptibles at time t, $p_S(t) = \Pr(S$ susceptibles at time $t)$. In a small time interval, $\mathrm{d}t$, such that the probability of more than one infection is negligible, two outcomes are possible: one new infection with probability $\lambda\,\mathrm{d}tS$ or no new infection with probability $1 - \lambda\,\mathrm{d}tS$. Therefore, the process can be expressed as

$$p_S(t+\mathrm{d}t) = p_S(t)(1-\lambda \mathrm{d}tS) + p_{S+1}(t)\lambda \mathrm{d}t(S+1). \tag{3.2}$$

As $\mathrm{d}t$ tends to zero, this yields the differential equation

$$\frac{\mathrm{d}p_S(t)}{\mathrm{d}t} = -\lambda S p_S(t) + \lambda(S+1)p_{S+1}(t). \tag{3.3}$$

This can be solved using a numerical approach in which the process is considered to consist of a series of infection events where the susceptible population decreases by one in each case. As shown by Renshaw (1991), for a population of S susceptibles and a disease that can be approximated by an exponential dose–response, the time T to the next event is an exponentially distributed random variable with

$$\Pr(T \geq t) = \exp(-\lambda S t). \tag{3.4}$$

This can be used to simulate the time to the next event, t, using a random number $0 \leq Y \leq 1$ by the equation

$$t = -\frac{\ln(Y)}{(\lambda S)}. \tag{3.5}$$

With λ defined by equation (3.1), the result in equation (3.5) can be easily applied to derive a series of inter-event times corresponding to the new cases of infection among the susceptible population in a ventilated indoor environment.

To account for the proximity of an infector to susceptibles and the incomplete mixing in interconnected ward spaces, the above model is applied within a zonal ventilation model. Here the air within each zone is treated as uniformly mixed; however, the mixing between the zones is limited. The infectious quanta is treated as a deterministic variable leading to a concentration distribution throughout the ward space. A simplified approach is applied which represents a realistic spatial arrangement of a ward but uses fixed interzonal ventilation rates to model transfer into and out of zones rather than environment-specific pressure coefficients. It must be highlighted that this approach is used only to demonstrate the behaviour of the stochastic risk model in a multi-zone space and the results are a considerable simplification of reality. However, it is straightforward to apply the approach described here using any ventilation network model or CFD simulation to assess the spatial distribution of infectious material in a real situation.

For the general case shown schematically in figure 1, the concentration of infectious material in the ith zone C_i can be approximated by considering the generation, ventilation removal and interzonal transfers for each case to give

$$V_i \frac{\mathrm{d}C_i}{\mathrm{d}t} = q_i I_i - Q_{oi} C_i - \sum_k \beta_{ik} C_i + \sum_k \beta_{ki} C_k. \tag{3.6}$$

Here, the term $q_i I_i$ represents the generation rate in the zone, Q_{oi} is the extract ventilation rate in zone i and β_{ik} and β_{ki} represent the volume flow rate of air to and from adjacent zones k, respectively. These interzonal flow rate terms consist of two components: a global mixing rate β_o which is a constant value in both directions across all zonal boundaries in the model plus an additional component β_{Qik} which expresses the net flow across a boundary owing to a ventilation imbalance between the two zones (Brouns & Waters 1991). This component is specific to the ventilation system and is defined for each boundary in the model to give the

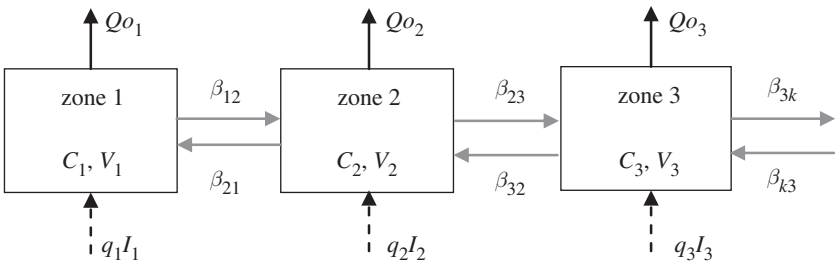

Figure 1. Schematic representation of simple zonal model for three adjacent zones. Solid black arrows indicate ventilation extract, solid grey arrows indicate interzonal flows, dashed black arrows indicate infection source within the zone.

total interzonal flow rate as

$$\beta_{ik} = \beta_o + \beta_{Qik}. \tag{3.7}$$

Under steady-state conditions, equation (3.6) is equal to zero for each zone and yields a set of equations that can be represented in matrix form and solved through a Gaussian elimination technique. This is shown partially below for the simple schematic case in figure 1:

$$\begin{bmatrix} -(Q_{o1}+\beta_{12}) & \beta_{21} & 0 & \cdots \\ \beta_{12} & -(Q_{o2}+\beta_{21}+\beta_{23}) & \beta_{32} & \cdots \\ 0 & \beta_{23} & -(Q_{o3}+\beta_{32}+\beta_{3k}) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ \vdots \end{bmatrix} = \begin{bmatrix} q_1I_1 \\ q_2I_2 \\ q_3I_3 \\ \vdots \end{bmatrix}. \tag{3.8}$$

The infection risk model is made zone dependent by replacing the term qI/Q with the zone concentration C_i from the solution of equation (3.8), giving

$$\lambda_i = C_i p. \tag{3.9}$$

As the new infection may now occur in any one of the occupied zones within the model, it is necessary to examine the relative probability of infection in each to determine in which zone each infection event occurs. At each time step, the probability that the next infection event will be in zone i is given by

$$\Pr(\text{infection in zone } i) = \frac{\lambda_i S_i}{R(k)},$$

where

$$R(k) = \sum_{k=1}^{9} \lambda_k S_k, \tag{3.10}$$

with the inter-event time now given by

$$t = -\frac{\ln(Y)}{R(k)}. \tag{3.11}$$

The numerical simulation of this process again follows the methodology described by Renshaw (1991)

(i) Calculation of $\lambda_i S_i/R(k)$ for each zone at the current time step.

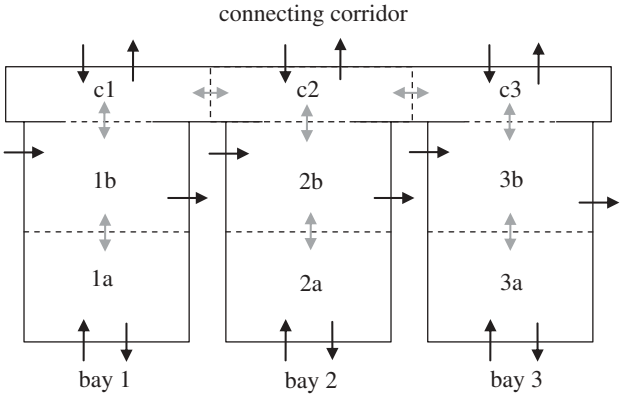

Figure 2. Hypothetical ward layout used in the study showing possible ventilation supply/extract (black arrows) and interzonal mixing (grey arrows).

(ii) Generation of a first random number $0 \leq Y \leq 1$ to find the inter-event time.
(iii) Generation of a second random number $0 \leq X \leq 1$ to establish which zone is infected based on infection in zone 1 if $0 \leq X \leq \lambda_1 S_1/R(k)$, zone 2 if $\lambda_1 S_1/R(k) \leq X \leq \lambda_2 S_2/R(k)$, etc.
(iv) Change S_i to S_{i-1} in infected zone i.

The model was implemented using Excel and VBA (Microsoft) incorporating a Monte Carlo approach to enable each model to run up to 100 times to calculate mean behaviour and the s.d. As the equations are defined in terms of inter-event times, which are different in every simulation owing to the random number in the event time definition, it was necessary to map each result onto a regular time scale in order to be able to find average data across more than one simulation. The simulations were mapped onto a 170 h time period divided into hourly steps, then plotted every 3 h to enable the data to be seen clearly.

4. RESULTS

The models described above were used to investigate the influence of population and airflows on the risk of infection through a parametric study approach. The model was based on a hypothetical hospital ward layout as shown in figure 2 comprising three identical six-bedded bays that open out onto a common corridor. To investigate a range of possible ventilation scenarios, each bay is divided into two equal zones

Table 1. Volume flow rate in and out of each zone for the six ventilation regimes.

	zones 1a, 2a, 3a		zones 1b, 2b, 3b		zones c1, c2, c3	
regime	supply ($m^3\,min^{-1}$)	extract ($m^3\,min^{-1}$)	supply ($m^3\,min^{-1}$)	extract ($m^3\,min^{-1}$)	supply ($m^3\,min^{-1}$)	extract ($m^3\,min^{-1}$)
A	3	3	3	3	3	3
B	9	0	0	0	0	9
C	0	9	0	0	9	0
D	6	6	0	0	3	3
E	6	0	0	6	3	3
F	0	6	6	0	3	3

(each containing three occupants) and the corridor split into three equal zones corresponding to the adjacent ward. The model assumes that ventilation air can be supplied and/or extracted from each zone and there is some degree of mixing between adjacent zones that is influenced by the ventilation regime as described above. All cases simulated a ward occupancy of 18 patients (six per bay) of which one located in zone 1a was assumed to be infectious. All patients were equally susceptible and breathed the ward air at a constant rate of $0.01\,m^3\,min^{-1}$ ($10\,l\,min^{-1}$). Six different ventilation regimes were investigated as detailed in table 1 to explore the effect of directional airflow. Although these specified different supply and extract volumes to the various zones, the total ventilation rate over the whole ward was $27\,m^3\,min^{-1}$ in all cases, equivalent to an average air change rate of $3\,AC\,h^{-1}$.

The interzone mixing parameter β_o was constant across all zone boundaries with a value between 9 and $27\,m^3\,min^{-1}$ depending on the simulation. The ventilation-dependent component of the interzone mixing β_{Qik} was defined to simulate directional airflow induced by a ventilation regime.

The final parameter is the value of quanta generation, which is particularly difficult to define for most infections. Previous researchers have estimated the values from outbreak data using equation (2.1) and the actual number of new cases. Most of the values given in the literature relate to TB outbreaks and the data collated in Beggs *et al.* (2003) indicate that for most pulmonary TB cases, a generation rate of between 1.25 and 60 quanta h^{-1} can be assumed. Higher values of hundreds or even thousands of quanta per hour are associated with medical procedures, such as bronchoscopy or abscess irrigation where the generation rate of infectious aerosols is increased. Riley *et al.* (1978) calculated a value of 570 quanta h^{-1} for a school measles outbreak, while Rudnick & Milton (2003) estimated quanta production rates for rhinovirus as 1–10 quanta h^{-1} and influenza as 15–128 quanta h^{-1}. For the purposes of this study, a quanta production rate of 0.5 quanta min^{-1} (30 quanta h^{-1}) is used. As the aim of this study is to examine the relative impact of the occupant and airflow parameters on the risk of infection, the actual quanta production rate is not critical. However, we will return to the definition and calculation of quanta in §5, as the model results raise some important questions about estimating quanta, and hence risk, from equation (2.1).

4.1. Stochastic effects

Prior to considering the effect of ventilation parameters, figures 3 and 4 compare the zonal and stochastic behaviour with a fully mixed deterministic simulation using equation (2.1) for a single infector generating 30 quanta h^{-1}. Figure 3 compares both approaches for the fully mixed case, presented in terms of a mean value with error bars indicating 1 s.d. In the stochastic model this is based on the data from 100 simulations, while in the deterministic solution, mean and s.d. are based on the Poisson assumption used in the derivation of equation (2.1). As such, the number of cases is taken as the Poisson mean and s.d. as the square root of the mean. As expected, the mean values from both the models are almost identical and both show considerable variability in the mean result. However, the expected variance differs between approaches, with a similar range predicted after short time duration, but a greater deviation from the mean indicated by the deterministic solution over a longer time period. This difference is probably apparent because basing the variability on the mean value from the deterministic solution inherently assumes variability in all parameters of the model, while the variation in the stochastic solution is due solely to the small population.

In figure 4, the deterministic fully mixed mean is compared with the zonal model results for ventilation regime A and the infector located in zone 1a. In this case all zones have an equal supply and extract volume flow rate; therefore, the interzonal mixing is solely due to the value of β_o, with no additional transfer through ventilation imbalance ($\beta_{Qik} = 0$). Results presented show the effect of air mixing on the total number of new cases across the whole ward. With a value of $\beta_o = 9\,m^3\,s^{-1}$, the overall infection rate is much slower than the fully mixed model, with less than two-thirds of the predicted total number of cases after the 170 h time period. Increasing the mixing to $\beta_o = 27\,m^3\,s^{-1}$ increases the rate at which the infection spreads with now around 85 per cent of the fully mixed model. The figure again shows the considerable variability in a small population with considerable overlap between the range of results for the two mixing

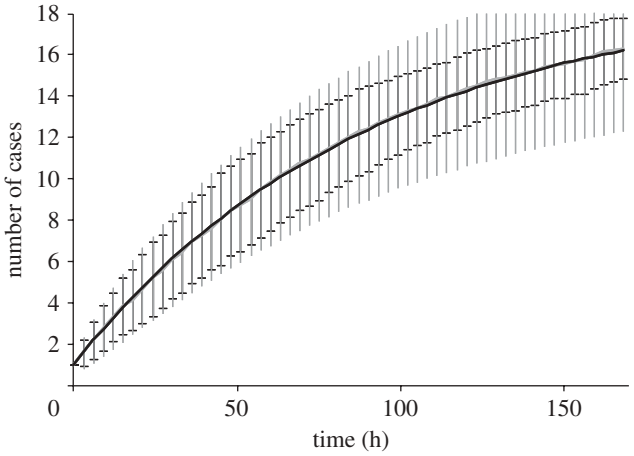

Figure 3. Comparison of variability from mean results in stochastic and deterministic fully mixed models. Error bars show 1 s.d. from the mean, with grey capped error bars for the stochastic model and black uncapped error bars for the deterministic model.

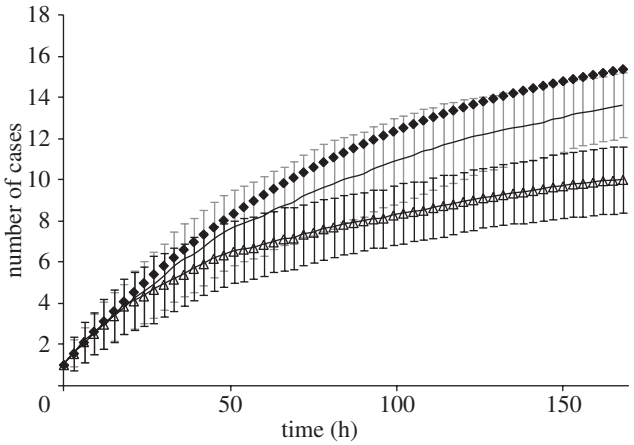

Figure 4. Effect of air mixing on the total rate of infection. Error bars show 1 s.d. from the mean value. Solid line denotes $\beta_o = 27\ \mathrm{m^3\ min^{-1}}$; open triangle denotes $\beta_o = 9\ \mathrm{m^3\ min^{-1}}$; filled diamond denotes fully mixed.

parameters and a deviation of approximately ± 15 per cent from the mean value in either stochastic simulation.

4.2. Effect of airflow paths

Although the results in figure 4 provide some initial insight into the potential influence of ventilation, the air mixing between the rooms is not influenced by the ventilation regime in this case. To understand the potential impact of this, simulations are run for all six ventilation regimes in table 1 using a fixed value of $\beta_o = 9\ \mathrm{m^3\ s^{-1}}$. In all cases, Monte Carlo simulations are performed with 100 simulation runs to yield mean infection rates for each of the three ward bays. The results from these simulations are presented in figure 5 in terms of infection risk, where a risk of one is equivalent to all six patients in a bay being infected.

The results in figure 5 demonstrate both the influence of proximity and ventilation flows on the risk

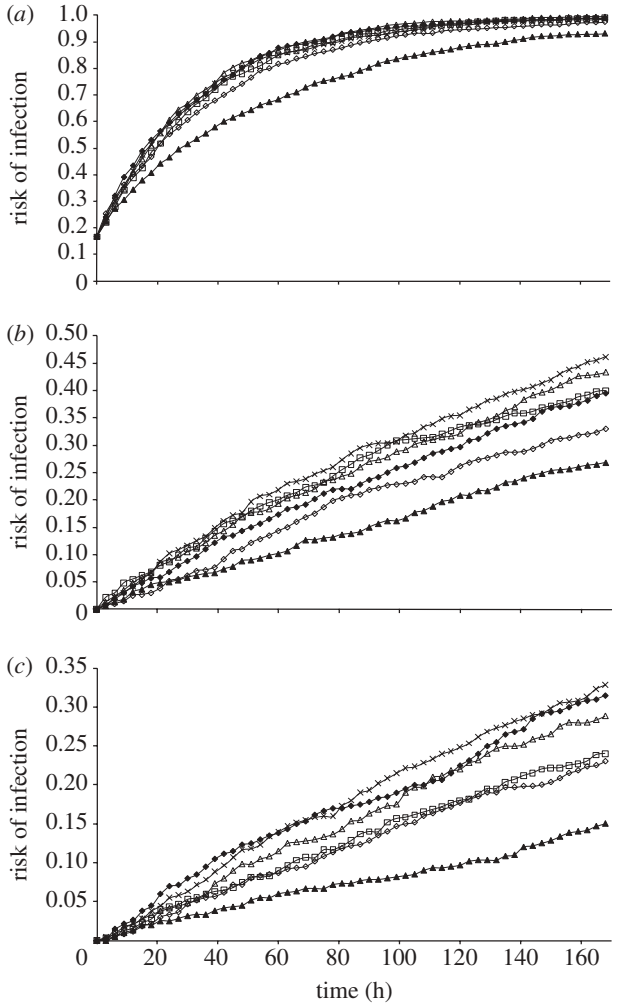

Figure 5. Effect of ventilation regime on the risk of infection over a 170 h period. Mean data obtained from 100 simulation runs. (*a*) Infections in bay 1. (*b*) Infections in bay 2. (*c*) Infections in bay 3. Filled diamonds, case A; open squares, case B; filled triangles, case C; crosses, case D; open triangles, case E; open diamonds, case F.

of infection for patients on the ward over time. As expected, the risk of infection in bay 1 (figure 5*a*), where the infector is located, is much higher than the other two bays, with the ventilation regime having little impact on the risk. Although ventilation regime C suggests a slightly lower infection rate compared with the other five regimes, the risk is still over 90 per cent over the 170 h period. The results for the other two bays (figure 5*b*,*c*), however, clearly demonstrate the potential impact of the ventilation system on the risk of airborne pathogen transfer throughout the space. In both cases, even with the stochastic variability in the data, the risk of infection is highest with ventilation regime D and lowest with regime C, with the risk around 50 per cent lower in bay 2 and 60 per cent lower in bay 3.

5. DISCUSSION

The results presented above give some initial insight into both the variability of infection risk likely to be

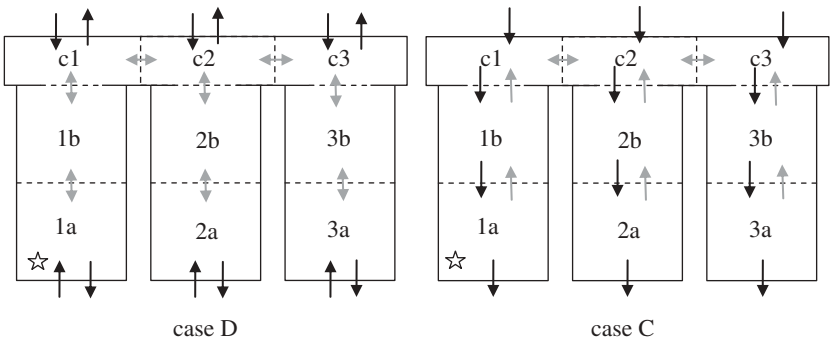

Figure 6. Schematic of ventilation flows in regimes D and C. Location of infector indicated by star. Black arrows indicate ventilation flow; grey arrows indicate interzonal mixing flows.

present in real situations as well as the role that ventilation flows may play in the transmission of infection.

The results in figures 3 and 4 clearly show that considering the stochastic variation produces a considerably wider range of predicted cases than the mean result typically derived from deterministic simulations. The model presented here indicates that the actual number of new infections could deviate from the mean by up to two cases owing to chance effects in a small population alone. As the results in figure 3 indicate, if there is uncertainty in other parameters, this could result in an even wider deviation. While the Wells–Riley model is a very straightforward approach for carrying out assessments as part of outbreak planning, the deterministic mean has the potential to significantly underestimate the bed numbers, staffing and resources needed to respond to an outbreak. As such some level of stochastic variability should be taken into account when using Wells–Riley type models in this way.

Hospital ventilation is typically designed on a mixing ventilation approach with little consideration beyond provision of adequate comfort except in certain applications such as isolation rooms, units for immunosuppressed patients or operating theatres. Although the zonal model presented here is a very simple representation of ventilation flows and is limited as a model of a real situation, the results do give some qualitative indication of the importance of airflow paths between zones in the transmission of infection. Many of the results are intuitive as can be seen by presenting the worst (D) and best (C) cases schematically in figure 6. In case C the air pathways are from the corridor to the ward, reducing the risk of airborne pathogens generated within a particular bay being transferred to other bays by extracting from the source location. However, in case D (and also cases A and E), the ventilation provides little or no additional movement of potential pathogens within the space. Although this does not actively promote the transfer between spaces, at the same time it does nothing to restrict it with little directional flow to limit transfer into other areas. These findings suggest that some approaches could be inadvertently contributing to the spread of infection and that careful design of a system could potentially provide greater protection for patients within a hospital ward.

The results presented in figure 5*a* suggest that case C also has some advantage in reducing within-bay transmission; however, this result should be treated with a good deal of caution. The results presented are the mean results from 100 stochastic simulations. The variability in the data plus the uncertainty over the exact location of the infector in the ward implies that, in reality, it is difficult to say from this model how the ventilation system impacts on the risk within a single bay. To understand the level of risk in this case more detailed simulations of the airflow, such as CFD analysis, are essential to show how the location of ventilation supply and extract vents influences the risk of cross-infection between patients (Noakes *et al.* 2006*b*).

Apart from giving some insight into the role of the ventilation system, the model applied above raises some important issues relating to the assessment of risk in indoor environments and use of quanta values in such activities. Regardless of the ventilation regime and layout, these results show a clear dependence of risk on the proximity to the infector. As shown by figure 5, with the values used in this hypothetical study patients in the same space as the infector have over a 90 per cent risk of infection over the 170 h period, while those two bays away (bay 3) have less than a 35 per cent risk over the same period. However, most quanta values quoted in the literature are calculated from outbreak data and do not consider the influence of proximity. The assumed value of 30 quanta h^{-1} with ventilation case A in the zonal stochastic model resulted in a mean number of infections across the whole ward of 10.2 in the 170 h period.

Quanta values presented in the literature take the total number of infections over a period of time, assume complete mixing and manipulate equation (2.1) to find the value for quanta production. In this case, using 10.2 new cases, 17 susceptibles in a fully mixed space with a total ventilation rate of 27 m^3 min^{-1} over 170 h, this yields a quanta production rate of 14.5 quanta h^{-1}, less than half the actual value. This suggests that using a fully mixed model to determine quanta production rates from outbreak data may significantly underestimate the quanta values in environments such as multi-zoned hospital wards or office buildings where the air will be far from fully mixed. In addition, using such values derived from outbreaks to estimate risk and design control procedures may significantly underestimate the actual risk, particularly for susceptible people in closer proximity to

the index case. Although shown here from a simple representation of the ventilation, the results concur with the findings of Qian *et al.* (2009) who showed differences between quanta values determined from mixed and spatially varying CFD models.

6. CONCLUSIONS

The Wells–Riley model has been used to examine airborne infectious disease transmission since the 1970s and remains a simple and valuable approach for understanding the role of various parameters to inform research, design and risk assessment. Linking the model with ventilation flows is a straightforward and practical option for those involved in the design and risk assessment of healthcare buildings. Provided users appreciate the limitations of the Wells–Riley model and their ventilation model, the approach enables a much greater understanding of the possible spatial transmission of infection and allows design and operational control strategies to be explored. The importance of stochastic effects, especially in small populations, should not be underestimated and users should seek to incorporate this into any model to evaluate the potential range of risk.

Coupling the model with disease dynamics, vaccination and environmental control strategies have also been tackled in previous studies and shown to give greater insight into the role of environmental and management strategies, particularly for the transmission of short incubation period diseases. The greatest uncertainty in the Wells–Riley model remains the disease parameters, with the concept of quanta suitable for parametric studies but severely limited in real risk assessments owing to the necessity to derive expected values from prior outbreaks. However, recent developments are showing considerable promise for establishing new methodologies for evaluating airborne disease transmission based on the dose–response characteristics of real pathogens. While this is currently limited by available time–dose data relevant to human subjects (Pujol *et al.* 2009), the right collaboration between those conducting experimental dosing studies and the infection risk modelling community could significantly enhance knowledge of disease characteristics and the pathogen–host interaction. Linking such knowledge to models incorporating environmental parameters offers a very effective framework for future assessment of airborne disease transmission in indoor environments.

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REFERENCES

Allen, K. D. & Green, H. T. 1987 Hospital outbreak of multiresistant *Acinetobacter anitratus*: an airborne mode of spread? *J. Hosp. Infect.* **9**, 110–119. (doi:10.1016/0195-6701(87)90048-X)

Armstrong, T. W. & Haas, C. N. 2007*a* A quantitative microbial risk assessment model for Legionnaires' disease: animal model selection and dose-response modelling. *Risk Anal.* **27**, 1581–1596. (doi:10.1111/j.1539-6924.2007.00990.x)

Armstrong, T. W. & Haas, C. N. 2007*b* Quantitative microbial risk assessment model for Legionnaires' disease: assessment of human exposures for selected spa outbreaks. *J. Occup. Environ. Hyg.* **4**, 634–646. (doi:10.1080/15459620701487539)

Asfour, O. S. & Gadi, M. B. 2007 A comparison between CFD and network models for predicting wind-driven ventilation in buildings. *Build. Environ.* **42**, 4079–4085. (doi:10.1016/j.buildenv.2006.11.021)

Bailey, N. T. 1957 *The mathematical theory of epidemics.* London, UK: Griffin & Co.

Bartrand, T. A., Weir, M. H. & Haas, C. N. 2008 Dose-response models for inhalation of *Bacillus anthracis* spores: interspecies comparisons. *Risk Anal.* **28**, 1115–1124. (doi:10.1111/j.1539-6924.2008.01067.x)

Beggs, C. B., Noakes, C. J., Sleigh, P. A., Fletcher, L. A. & Siddiqi, K. 2003 The transmission of tuberculosis in confined spaces: an analytical study of alternative epidemiological models. *Int. J. Tuberc. Lung Dis.* **7**, 1015–1026.

Brouns, C. & Waters, B. 1991 A guide to contaminant removal effectiveness. AIVC technical note 28.2, Air Infiltration and Ventilation Centre, Belgium.

Chen, Q. 2009 Ventilation performance prediction for buildings: a method overview and recent applications. *Build. Environ.* **44**, 848–858. (doi:10.1016/j.buildenv.2008.05.025)

Chen, S. C. & Liao, C. M. 2008 Modelling control measures to reduce the impact of pandemic influenza among schoolchildren. *Epidemiol. Infect.* **136**, 1035–1045.

Chen, S. C., Chio, C. P., Jou, L. J. & Liao, C. M. 2009 Viral kinetics and exhaled droplet size affect indoor transmission dynamics of influenza infection. *Indoor Air* **19**, 401–413. (doi:10.1111/j.1600-0668.2009.00603.x)

Chow, T. T. & Yang, X. Y. 2004 Ventilation performance in the operating theatre against airborne infection: review of research activities and practical guidance. *J. Hosp. Infect.* **56**, 85–93. (doi:10.1016/j.jhin.2003.09.020)

Escombe, A. R. *et al.* 2007 The detection of airborne transmission of tuberculosis from HIV-infected patients using an *in vivo* air sampling model. *Clin. Infect. Dis.* **44**, 1349–1357. (doi:10.1086/515397)

Escombe, A. R. *et al.* 2009 Upper-room ultraviolet light and negative air ionization to prevent tuberculosis transmission. *PLoS Med.* **6**, e1000043. (doi:10.1371/journal.pmed.1000043)

Farrington, M., Ling, J., Ling, T. & French, G. L. 1990 Outbreaks of infection with methicillin-resistant *Staphylococcus aureus* on neonatal and burns units of a new hospital. *Epidemiol. Infect.* **105**, 215–228. (doi:10.1017/S0950268800047828)

Fennelly, K. P., Davidow, A. L., Miller, S. L., Connell, N. & Ellner, J. J. 2004 Airborne infection with *Bacillus anthracis*: from mills to mail. *Emerg. Infect. Dis.* **10**, 996–1001.

Gammaitoni, L. & Nucci, M. C. 1997 Using a mathematical model to evaluate the efficacy of TB control measures. *Emerg. Infect. Dis* **3**, 335–342. (doi:10.3201/eid0303.970310)

Haas, C. N. 1983 Estimation of risk due to low doses of microorganisms: a comparison of alternative methodologies. *Am. J. Epidemiol.* **118**, 1097–1100.

Hu, B., Freihaut, J. D., Bahnfleth, W. P., Aumpansub, P. & Thran, B. 2007 Modeling particle dispersion under human activity disturbance in a multizone indoor environment. *J. Arch. Eng.* **13**, 187–193. (doi:10.1061/(ASCE)1076-0431(2007)13:4(187))

Huang, Y. & Haas, C. N. 2009 Time-dose-response models for microbial risk assessment. *Risk Anal.* **29**, 648–661. (doi:10.1111/j.1539-6924.2008.01195.x)

Jones, R. M., Masago, Y., Bartrand, T. A., Haas, C. N., Nicas, M. & Rose, J. B. 2009 Characterizing the risk of infection from *Mycobacterium tuberculosis* in commercial passenger aircraft using quantitative microbial risk assessment. *Risk Anal.* **29**, 355–365. (doi:10.1111/j.1539-6924.2008.01161.x)

Ko, G., Thompson, K. M. & Nardell, E. A. 2004 Estimation of tuberculosis risk on a commercial airliner. *Risk Anal.* **24**, 379–388. (doi:10.1111/j.0272-4332.2004.00439.x)

Kumari, D. N. P., Haji, T. C., Keer, V., Hawkey, P. M., Duncanson, V. & Flower, E. 1998 Ventilation grilles as a potential source of methicillin-resistant *Staphylococcus aureus* causing an outbreak in an orthopaedic ward at a district general hospital. *J. Hosp. Infect.* **39**, 127–133. (doi:10.1016/S0195-6701(98)90326-7)

Li, Y., Huang, X., Yu, I. T. S., Wong, T. W. & Qian, H. 2005 Role of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong. *Indoor Air* **15**, 83–95. (doi:10.1111/j.1600-0668.2004.00317.x)

Lipsitch, M. *et al.* 2003 Transmission dynamics and control of severe acute respiratory syndrome. *Science* **300**, 1966–1970. (doi:10.1126/science.1086616)

Mara, D. D., Sleigh, P. A., Blumenthal, U. J. & Carr, R. M. 2007 Health risks in wastewater irrigation: comparing estimates from quantitative microbial risk analyses and epidemiological studies. *J. Water Health* **5**, 39–50. (doi:10.2166/wh.2006.055)

Mertens, R. A. F. 1996 Methodologies and results of national surveillance. *Bailliere's Clin. Infect. Dis.* **3**, 159–178.

Mora, L., Gadgil, A. J. & Wurtz, E. 2003 Comparing zonal and CFD model predictions of isothermal indoor airflows to experimental data. *Indoor Air* **13**, 77–85. (doi:10.1034/j.1600-0668.2003.00160.x)

Morse, S. S., Garwin, R. L. & Olsiewski, P. J. 2006 Next flu pandemic: what to do until the vaccine arrives? *Science* **314**, 929. (doi:10.1126/science.1135823)

Nardell, E. A., Keegan, J., Cheney, S. A. & Etkind, S. C. 1991 Airborne infection: theoretical limits of protection achievable by building ventilation. *Am. Rev. Resp. Dis.* **144**, 302–306.

Nicas, M. & Hubbard, A. 2002 A risk analysis for airborne pathogens with low infectious doses: application to respirator selection against *Coccidioides immitis* spores. *Risk Anal.* **22**, 1153–1163. (doi:10.1111/1539-6924.00279)

Noakes, C. J., Beggs, C. B. & Sleigh, P. A. 2004*a* Modelling the performance of upper room ultraviolet germicidal irradiation devices in ventilated rooms: comparison of analytical and CFD methods. *Indoor Built Environ.* **13**, 477–488. (doi:10.1177/1420326X04049343)

Noakes, C. J., Fletcher, L. A., Beggs, C. B., Sleigh, P. A. & Kerr, K. G. 2004*b* Development of a numerical model to simulate the biological inactivation of airborne microorganisms in the presence of ultraviolet light. *J. Aerosol Sci.* **35**, 489–507. (doi:10.1016/j.jaerosci.2003.10.011)

Noakes, C. J., Beggs, C. B., Sleigh, P. A. & Kerr, K. G. 2006*a* Modelling the transmission of airborne infections in enclosed spaces. *Epidemiol. Infect.* **134**, 1082–1091. (doi:10.1017/S0950268806005875)

Noakes, C. J., Sleigh, P. A., Escombe, A. R. & Beggs, C. B. 2006*b* Use of CFD analysis in modifying a TB ward in Lima, Peru. *Indoor Built Environ.* **15**, 41–47. (doi:10.1177/1420326X06062364)

Pujol, J. M., Eisenberg, J. E., Haas, C. N. & Koopman, J. S. 2009 The effect of ongoing exposure dynamics in dose response relationships. *PLoS Comp. Biol.* **5**, e1000399. (doi:10.1371/journal.pcbi.1000399)

Qian, H., Li, Y. G., Nielsen, P. V. & Huang, X. H. 2009 Spatial distribution of infection risk of SARS transmission in a hospital ward. *Build. Environ.* **44**, 1651–1658. (doi:10.1016/j.buildenv.2008.11.002)

Renshaw, E. 1991 *Modelling biological populations in space and time* (eds C. Cannings, F. C. Hoppensteadt & L. A. Segel). Cambridge, UK: Cambridge University Press.

Riley, E. C., Murphy, G. & Riley, R. L. 1978 Airborne spread of measles in a suburban elementary school. *Am. J. Epidemiol.* **107**, 421–432.

Riley, S. *et al.* 2003 Transmission dynamics of the etiological agent of SARS in Hong Kong: impact of public health interventions. *Science* **300**, 1961–1966. (doi:10.1126/science.1086478)

Rudnick, S. N. & Milton, D. K. 2003 Risk of airborne infection transmission estimated from carbon dioxide concentration. *Indoor Air* **13**, 237–245. (doi:10.1034/j.1600-0668.2003.00189.x)

Scales, D. C. *et al.* 2003 Illness in intensive care staff after brief exposure to severe acute respiratory syndrome. *Emerg. Infect. Dis.* **9**, 1205–1210.

Siegel, J. D., Rhinehart, E., Jackson, M., Chiarello, L. & Healthcare Infection Control Practices Advisory Committee. 2007 Guideline for isolation precautions: preventing transmission of infectious agents in healthcare settings. See http://www.cdc.gov/ncidod/dhqp/pdf/isolation2007.pdf.

Wells, W. F. 1955 *Airborne contagion and air hygiene.* Cambridge, MA: Harvard University Press.

Yu, I. T. S., Li, Y. G., Wong, T. W., Tam, W., Chan, A. T., Lee, J. H. W., Leung, D. Y. C. & Ho, T. 2004 Evidence of airborne transmission of the severe acute respiratory syndrome virus. *N. Engl. J. Med.* **350**, 1731–1739. (doi:10.1056/NEJMoa032867)

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Assessing the effects of transient weather conditions on airborne transmission risk in naturally ventilated hospitals

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SUMMARY

Background: Many UK hospitals rely heavily on natural ventilation as their main source of airflow in patient wards. This method of ventilation can have cost and energy benefits, but it may lead to unpredictable flow patterns between indoor spaces, potentially leading to the unexpected transport of infectious material to other connecting zones. However, the effects of weather conditions on airborne transmission are often overlooked.

Methods: A multi-zone CONTAM model of a naturally ventilated hospital respiratory ward, incorporating time-varying weather, was proposed. Coupling this with an airborne infection model, this study assessed the variable risk in interconnected spaces, focusing particularly on occupancy, disease and ventilation scenarios based on a UK respiratory ward.

Results: The results suggest that natural ventilation with varying weather conditions can cause irregularities in the ventilation rates and interzonal flow rates of connected zones, leading to infrequent but high peaks in the concentration of airborne pathogens in particular rooms. This transient behaviour increases the risk of airborne infection, particularly through movement of pathogens between rooms, and highlights that large outbreaks may be more likely under certain conditions. This study demonstrated how ventilation rates achieved by natural ventilation are likely to fall below the recommended guidance, and that the implementation of supplemental mechanical ventilation can increase ventilation rates and reduce the variability in infection risks.

Conclusion: This model emphasises the need for consideration of transient external conditions when assessing the risk of transmission of airborne infection in indoor environments.

Introduction

Airborne transmission is an infection route for many pathogens, including severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2), influenza viruses, measles virus

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and *Mycobacterium tuberculosis* [1]. Transmission is strongly influenced by ventilation and indoor airflow [2,3], and this includes air movement to connected spaces, possibly causing infections in spaces where the infectious person is not present. Reducing the risk of airborne transmission is especially important on respiratory wards as patients are particularly vulnerable, there is high prevalence of lung infections caused by potential airborne pathogens, and respiratory disease is a major contributor to pressure on hospital systems [4].

UK guidance states that most hospital wards should have fresh air ventilation rates of 6 air changes per hour (ACH) [5]. However, a large proportion of wards rely on natural ventilation, usually by opening windows, making the ventilation rate highly dependent on weather conditions and the opening sizes of windows, doors or leakage [6]. Natural ventilation is wind driven, governed by wind speed and direction, or stack driven, governed by temperature differences [7]. These modes can work together or sometimes counteract one another, making natural ventilation an ambiguous method of ventilation [8]. Experimental studies in healthcare settings have reported a large variation in natural ventilation rates, ranging from 3.4 to 6.5 ACH with windows open in a UK Nightingale ward [9] to extremely high levels of ventilation up to 28 ACH in Peru [10] or 69 ACH in Hong Kong [11]. However, these studies were for single spaces with good openings, and all discussed how natural ventilation is uncertain and difficult to control, suggesting that mechanical ventilation may be more reliable [9,11]. Natural ventilation is highly dependent on occupant behaviour [6,11], and is reduced substantially if the occupant responds to external conditions by closing windows or doors [12—14]. Additional factors which reduce efficiency include safety features that restrict window opening, and reducing wall vents and leakage to improve energy efficiency [9].

Mathematical models are useful to understand the risk of infection in indoor spaces, but the majority of the current models consider single-zone spaces and overlook the importance of transient weather and occupancy effects [15]. Studies have begun to consider multi-zone approaches [15—17], and express the importance of connected spaces when considering airborne contaminant transport [18,19], with more recent work providing evidence of transmission to neighbouring zones [20,21]. CONTAM software [22,23] is commonly used to simulate contaminant transport directly within multi-zone indoor environments [14,24—26], or as a tool for airflow simulation alone, which can then be used in other models, such as a state-space model [27], to assess mitigation strategies [28,29] or to evaluate the risk of infection [30]. Previous studies have considered the impact of seasonality and weather conditions on disease transmission [13,25,31—38], and suggest the need to use varying weather effects within models. The majority of zonal models use steady-state weather conditions, including for contaminant transport in hospitals [39], offices [29] and dwellings [19,40]. More recent studies have begun to analyse the effects of using transient weather conditions to assess contaminant transport, such as using CONTAM software in dwellings [26,41,42]. Zhu *et al.* [43] used CONTAM software to conduct a whole-building simulation of two college halls of residence with transient weather conditions to model respiratory infections, with the use of measured Carbon Dioxide (CO_2) to validate the model; CO_2 has been used as a proxy for ventilation efficacy in calculating the risk of infection [44].

This study used a modelling approach to explore the likely variation in airborne infection risks due to external weather conditions in a multi-zone naturally ventilated respiratory ward. CONTAM software was used to simulate airflow, coupled with a previously developed susceptible-exposed-based transmission model [15]. Through this coupling, the effects of transient weather conditions on indoor airflow and risk of infection were assessed, applying the methodology to a specific fixed-occupancy scenario over longer time scales, and the variability in exposure to infection under different ventilation conditions was explored.

Methods

Airflow simulations

CONTAM 3.4.0.3 [22,23] was used to simulate the ventilation in a multi-zone hospital ward, based on a UK NHS hospital trust respiratory ward, which relies on natural ventilation through windows, doors and leakage as its main source of airflow. A 12-zone subset was selected to be representative of the space; this can be seen in Figure 1, showing room labels, volumes, building orientation and window location. The ward was representative of a typical layout of many UK hospitals, with a combination of multi-occupancy bays and single cubicles.

The CONTAM model set-up is described in detail in Supplementary Material A. Windows were assumed to remain open and doors closed for the full duration of the simulation. Corresponding leakage for the windows and doors in each zone represents small gaps present around these elements. Window open dimensions and model flow parameters considered the restricted openings present in NHS hospitals (Supplementary Table A1). Internal zones without windows (Zones 5—8) had an internal temperature of 25 °C. External zones with windows (Zones 1—4 and 9—12) had an internal temperature of 22 °C. For cases with additional mechanical ventilation, an air handling system is defined in CONTAM with a balanced supply and extract ventilation, so as not to create any new pressure differences in the ward.

The governing equations for the CONTAM simulation followed the methodology used in previous work [15] (Supplementary Material B.1). The airflow simulations were solved transiently over a 6-month period (1st April—30th September 2021), and the calculation time step was 30 min. A transient weather file for the Leeds area in 2021 [45] was used to represent the external environmental conditions throughout the simulation, such as ambient temperature, barometric pressure, wind speed and wind direction. The mean values in the weather data were air temperature of 10.18 °C, barometric pressure of 100,785.61 Pa, wind speed of 4.40 m/s and wind direction of 226.68° (south-westerly). A wind rose plot of the weather data is provided as Supplementary Figure C1. The only factors that varied within the simulations were weather conditions; all other conditions remained constant.

Transmission model

The airborne infection transmission model was adapted from the authors' previous work [15] (Supplementary Material B.2). The approach was based on the Wells—Riley equation, and assumes that an infectious individual emits a pathogen into

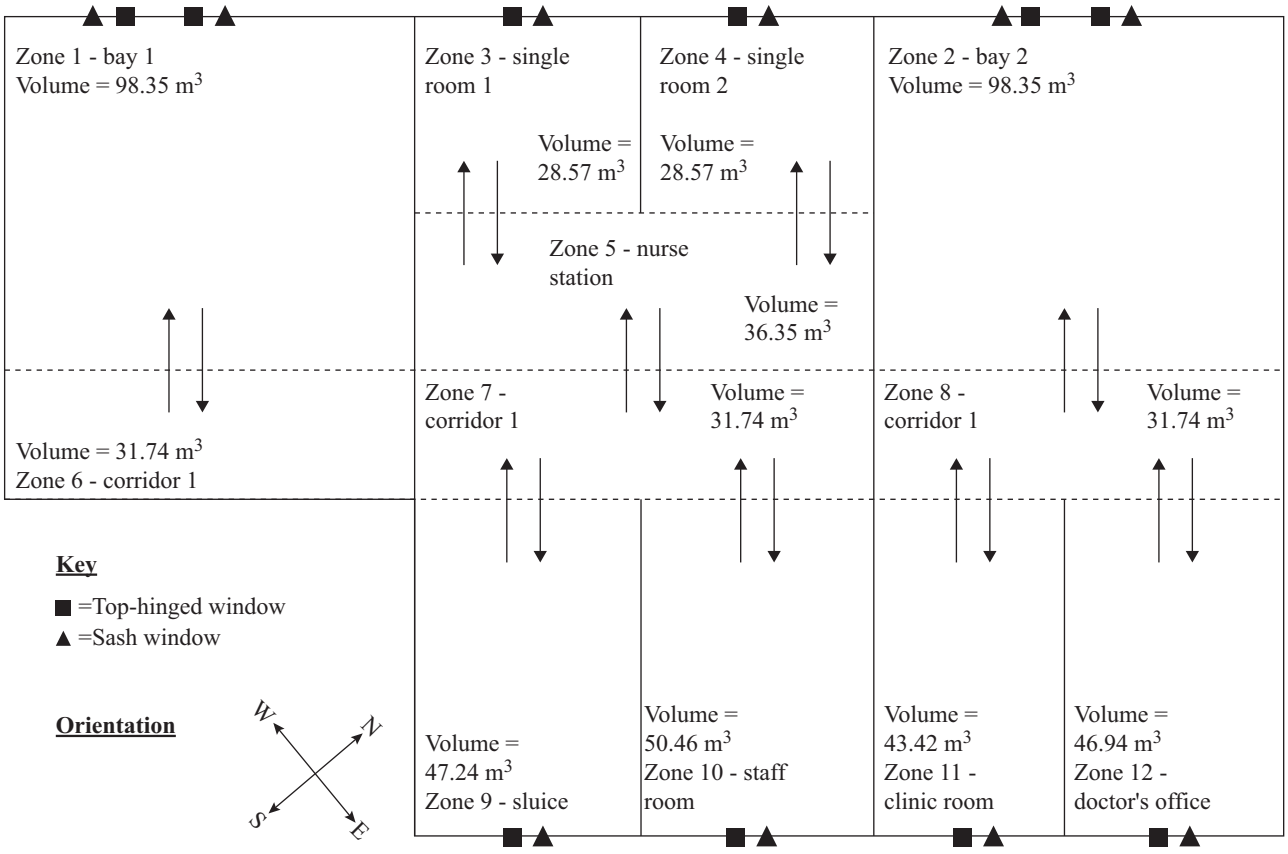

Figure 1. Twelve-zone subset of a UK respiratory ward showing the zone number, type and volume for each zone, orientation of the geometry, and location of windows. Modelled occupancy included four individuals in Zones 1 & 2, three individuals in Zone 10, two individuals in Zone 11, one individual in Zones 3, 4, 5 and 12, and zero individuals in Zones 6, 7, 8 and 9.

the air at a constant rate, defined as infectious doses or quanta per hour. The ventilation from the CONTAM model was used to determine the concentration of pathogen in air, which was linked to a pulmonary breathing rate to calculate exposure for susceptible individuals. To model transient variation in risk of infection, ventilation rates and interzonal airflow were exported from the CONTAM solution and used in the transmission model.

To assess the total number of predicted infection exposures, the simulation was split into weekly periods as the 6-month airflow simulation is an unrealistically long period to have a single infectious person present with no treatment or secondary infections emerging. The total predicted exposures from the model were recorded at the end of each week, considering whole-person exposures only, and then the initial conditions reset. This used the transient quanta concentration, calculated from the emission rate, airflow and corresponding weather conditions for that given week. This was repeated across the 26 weeks within the 6-month period of the simulation. These values were used to form a distribution, showing the probability of a particular number of exposures on a given week across the ward, assuming that one infected person was present for the duration of the week.

In addition to the probability distribution for predicted exposures, a risk index (RI) was calculated. The RI represents the average fraction of individuals exposed across the whole ward, and can be calculated using Equation (1).

$$\mathrm{RI} = E\left[\frac{E(t)}{n}\right] \tag{1}$$

where $E(t)$ is a random variable which represents the predicted number of exposures, and n represents the total number of susceptible people. To calculate RI, $P\{E(t) = x\}$ is used as the probability, as a proportion out of all 26 weeks, that $E(t) = x$ predicted whole-person exposures. This probability is then multiplied by x and divided by the total number of susceptible individuals present, n. This is done for all possible values of x, and then the sum is used, as indicated in Equation (2).

$$E\left[\frac{E(t)}{n}\right] = \sum_{x=0}^{n} \frac{x}{n} P\{E(t) = x\} \tag{2}$$

Results

Comparison with measured data

To ensure the modelled airflow was realistic, CO_2 values were simulated using CONTAM and compared against experimental data measured for a single internal zone (Zone 5) using an Airvisual pro sensor (IQAir) at 10-s intervals in October 2019. The sensor was located on the nursing station and recorded temperature, humidity, particulates and CO_2 continuously, although only the CO_2 data were used in this study. The sensor

range for CO_2 measurement is 400–10,000 parts per million (ppm) with accuracy of 70 ppm ±3% at temperatures up to 50 °C and relative humidity up to 95%. In the model, individuals present are sources of CO_2, with a generation rate of 0.005 L/s [46] and are assumed to be in a fixed location for the full duration of the simulation. Although this is unrealistic in terms of specific individuals being present at the same location for the full duration, it is representative of the average ward occupancy over that period e.g., if a patient is discharged or moved, it was assumed they were replaced. The outdoor ambient concentration of CO_2 was taken to be 400 ppm. Simulations were carried out for the October weather data for two cases: (i) with all doors closed; and (ii) with the patient zone doors closed (Zones 1, 2, 3 and 4) and other doors open. The CO_2 concentrations for simulated and measured data are plotted as a histogram, separated into three bins; 400–800 ppm, 800–1200 ppm and >1200 ppm (Figure 2).

Despite the fact that the authors were unable to model the exact transient occupancy, window opening behaviour or weather conditions that the real ward experienced, the simulated and measured data show very good agreement. In the case where only the patient zone doors were closed, a difference <±5.5% was seen, which was considered to be sufficiently close to conclude that the CONTAM model can represent the airflow realistically within this multi-zone space. Although this was not a full validation, due to the difficulty in replicating the exact conditions of the measured data, this offers reassurance that the airflow simulation captures the features of this hospital ward.

Transmission model analysis

The simulations assume one infectious individual in Zone 5, and 16 initially susceptible individuals across the ward. The quanta emission rate of the infector is $q_5 = 0.5$ quanta/min, and the pulmonary rate of all individuals is $p_k = 0.01$ m^3/min for all zones k [15,16]. The initial quanta concentration is $C_k(0) = 0$ in each zone.

Variability of natural ventilation

The first scenario considered the case where ventilation is provided solely by natural ventilation via the windows, and all doors are closed. Figure 3a shows the modelled transient concentration of airborne pathogen over the whole 6-month period (1st April–30th September 2021). Sharp peaks are a prominent feature, which suggests that particular hours or days may pose a higher risk of infection than others. As the transmission model imports the airflow from CONTAM, these peaks happen as a direct result of the airflow within the space, driven only by the transient weather conditions. To illustrate the frequency of peaks, a probability density histogram for the quanta concentration is shown in Figure 3b. The majority of values are <0.5 quanta/m^3, with only 4.57% of values above this threshold; the zoomed portion of this plot only represents 0.35% of all concentration values. This is useful in showing that, although these spikes may appear to be the dominant feature in Figure 3a, the highest concentration values are highly infrequent in comparison with the majority of concentration values over time.

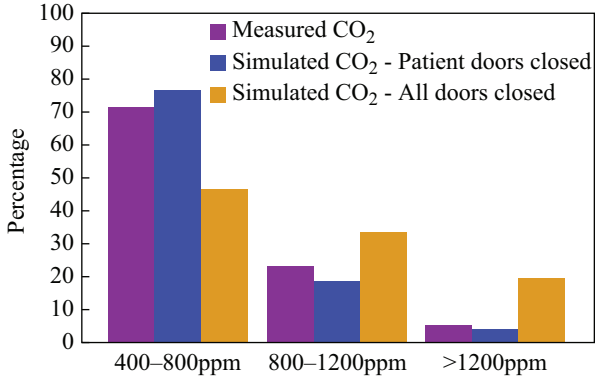

Figure 2. Comparison between simulated and measured CO_2 values for the month of October for Zone 5.

Figure 4a shows the predicted exposure distribution for a typical week, with the RI value [Equation (1)] superimposed. There is a relatively high risk of exposure across the ward, with the possibility of up to 12 of the susceptible population becoming exposed to infection. As the doors to each zone are closed, with the infector remaining fixed in one zone, the risk is driven solely by the interzonal airflow as a response to external conditions, leading to pathogen transport through the leakage around doors. This illustrates the importance of multi-zone models with connected airflow, as there may be a non-zero risk of transmission despite the absence of an infector. The large spread of the distribution, ranging from four to 12 individuals, suggests a significant variability in exposures, highlighting the uncertainty that is occurring due to the weather conditions. These results also suggest the possibility of elevated risk on particular days or weeks over the 6-month period, meaning that part of the risk experienced when visiting or being admitted to a hospital ward may be pre-determined by the weather.

In this scenario, RI = 0.5288, translating to 52.88% of individuals becoming exposed across the whole ward on a typical week. This appears to be a high value; however, it is a worst-case scenario, as it was assumed that the infector was present in the ward for the whole time period. In Figure 4b, the RI for each zone is illustrated as a heat map, giving an insight into the risk in each zone, rather than a ward as a whole. The RI for each zone is calculated using the zonal population as n in Equation (1), instead of the ward population, to give risk as a proportion of the number of people typically in the space. The variation in risk could be suggestive of a particular airflow pattern, where infectious material is more likely to be transported to particular zones. For example, Zone 10 has a considerably higher risk than the other zones, and also has a larger typical occupancy of three individuals compared with the other rooms. Similarly, Zone 2 experiences almost zero risk from the infector in Zone 5, but adjacent rooms have an elevated risk. The results here illustrate the uncertainty caused by natural ventilation, and the dominance of the weather conditions on determining the airflow and risk of airborne transmission in indoor environments.

Addition of mechanical ventilation

The effects of adding 3 ACH or 6 ACH mechanical ventilation alongside open windows, with all doors closed as before, were explored. The probability distribution for the predicted exposures, the overall ward RI, and the zonal RI heat map are shown in Figure 5. The results show a substantial reduction in risk,

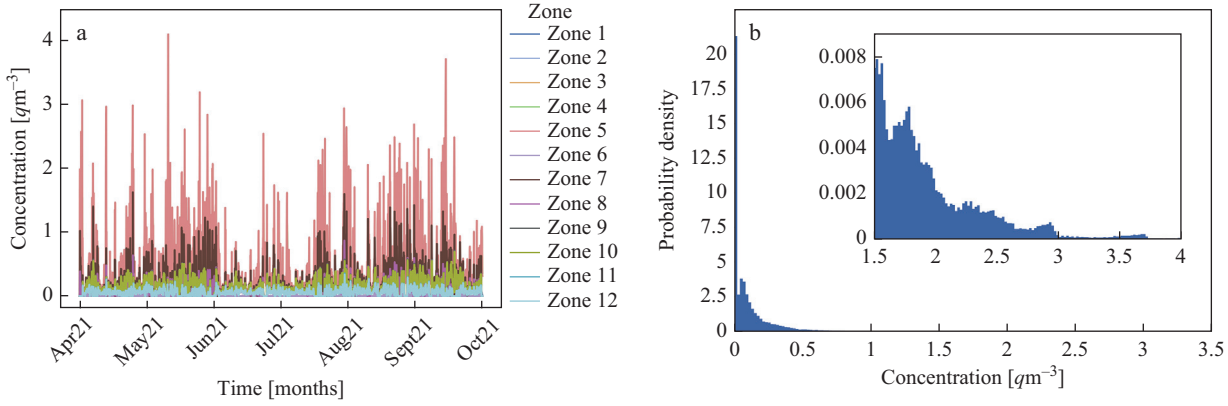

Figure 3. Simulated concentration of pathogen in the air for 'natural ventilation only'. (a) Concentration in each zone for a 6-month period; (b) probability density histogram of the quanta concentration values, with a zoomed portion showing the infrequent higher values.

with predicted exposures now ranging from zero to two individuals, illustrating a much smaller spread to the distribution and, thus, less uncertainty. With 3 ACH additional mechanical ventilation, the ward RI = 0.0769, which is >85% reduction compared with the original case. This can also be illustrated in the heat map (Figure 5b), suggesting that the virus would be better contained with less-affected zones and only one zone with risk >40% (compared with five zones in the original case). In the case with 6 ACH mechanical ventilation (Figure 5c), the recommended rate for NHS patient wards [5], RI is reduced to 0.0168, which is >96% lower than the original case, and an additional 11% reduction from the 3 ACH scenario. The zonal RI heat map (Figure 5d) indicates low risk across all zones, with only one zone having a non-zero risk (<9%).

The addition of mechanical ventilation contained the infectious quanta concentration and reduced pathogen transport more effectively than weather-driven natural ventilation alone, eliminating the uncertainty that was originally present. It is possible that, under some weather conditions, natural ventilation and the consequent airflow make a greater contribution to the transport of pathogen into connected spaces, rather than being efficient at the removal of the infectious quanta concentration. This further demonstrates that the effects seen in the original scenario were a direct consequence of the transient weather conditions. It is important to note that this is an idealised scenario, and, in reality, imperfect balancing of mechanical ventilation systems and the behaviour of people will likely mean that the difference between natural ventilation and mechanical ventilation is not as stark.

Ventilation rates

Figure 6a presents a probability density plot illustrating the ventilation rates predicted by the CONTAM model for a period of 6 months for the 'natural ventilation only' case and the 'natural ventilation + 3 ACH mechanical ventilation' case.

With natural ventilation alone, 82% of predicted ventilation rates fell below 1 ACH and 99.5% fell below 2 ACH, with the highest not surpassing 2.6 ACH, which is less than half of the recommended rate. The mean ventilation rate achieved across the ward is 0.61 ACH. The addition of 3 ACH mechanical ventilation resulted in the same shaped distribution as in the original case, but shifted to a higher value. However, ventilation rates still fell below the recommended rate of 6 ACH [5].

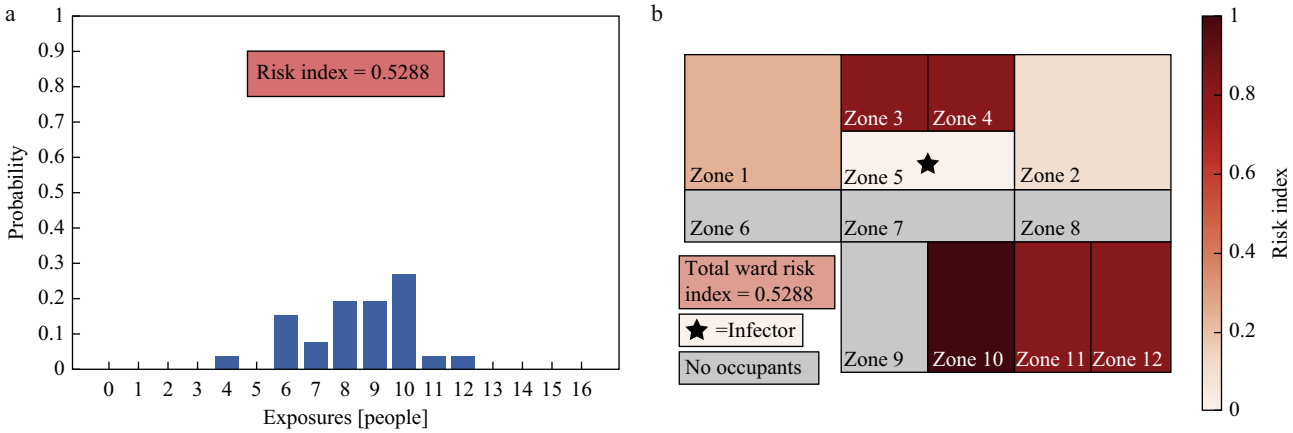

Figure 4. Predicted exposures for 'natural ventilation only'. (a) Probability distribution showing predicted weekly exposures and risk index across the whole ward; (b) heat map showing the zonal risk index value based on predicted exposure.

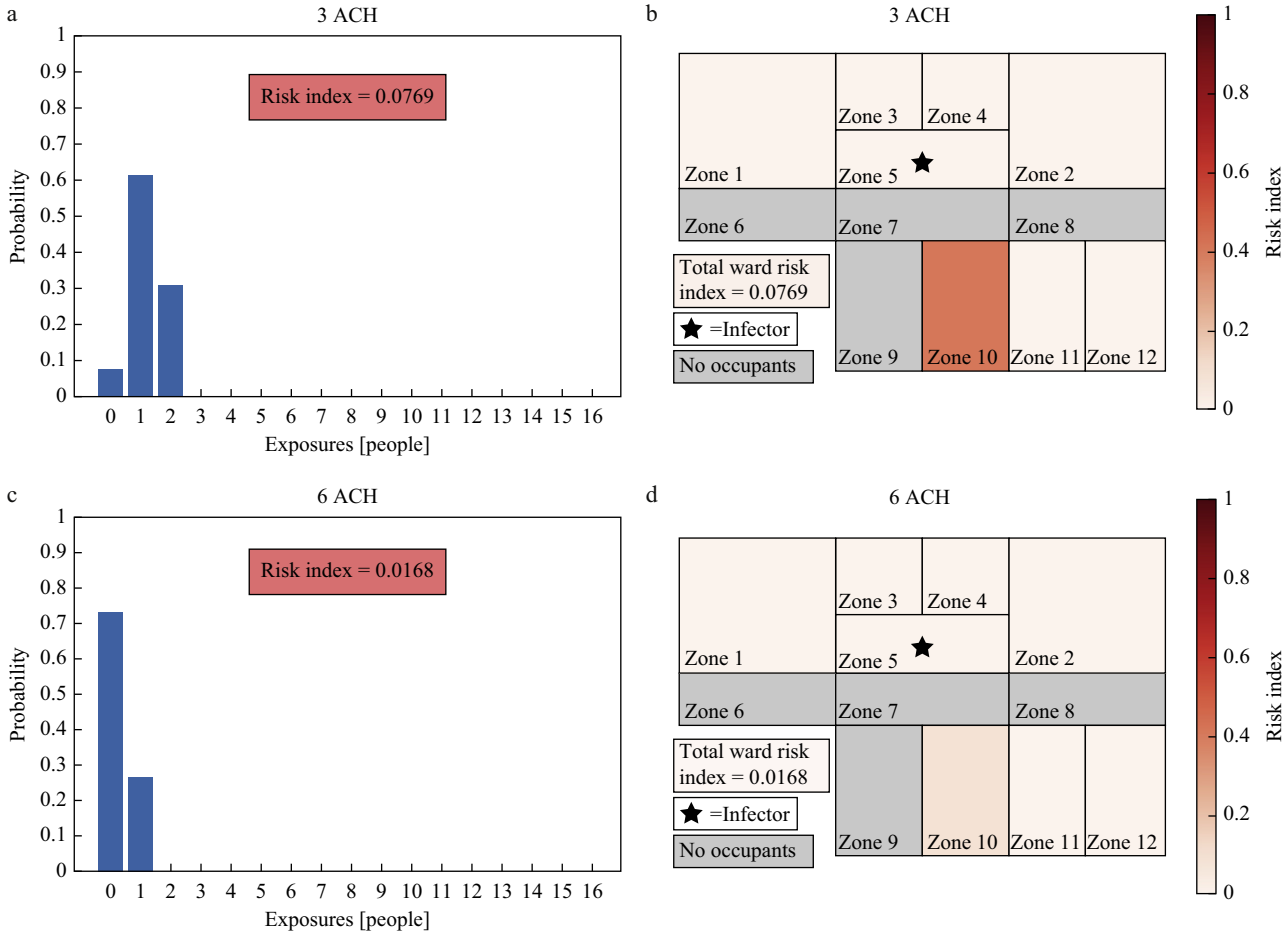

Figure 5. Predicted exposures with the addition of mechanical ventilation. (a,c) A weekly probability distribution across the whole ward together with the risk index value; (b,d) heat map showing the zonal risk index value based on predicted exposures. ACH, air changes per hour.

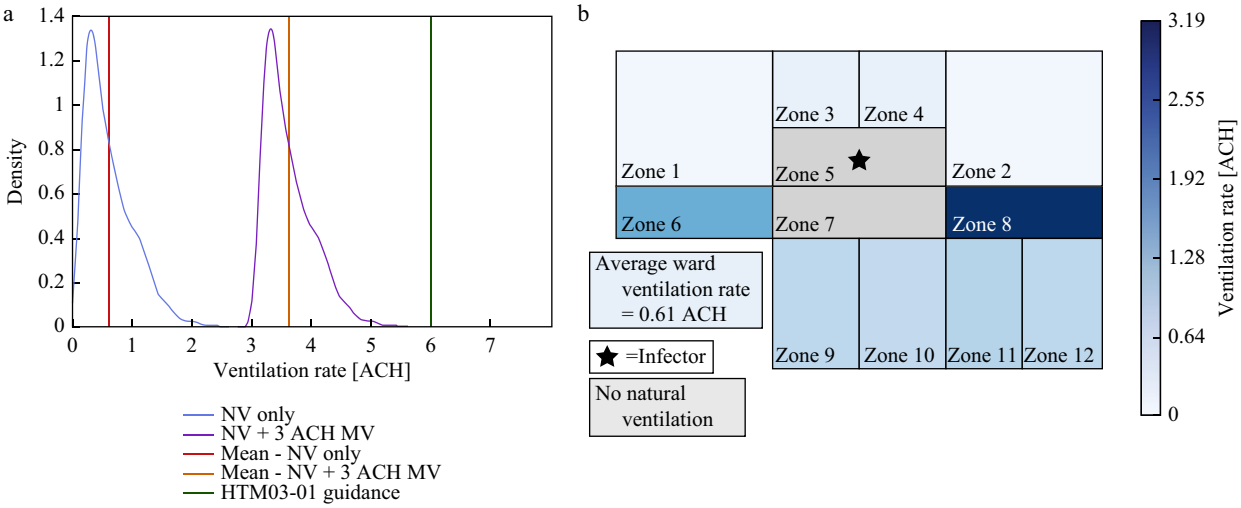

Figure 6. (a) Probability density plot showing the overall and mean ventilation achieved across the ward for both 'natural ventilation (NV) only' and 'natural ventilation + 3 air changes per hour (ACH) mechanical ventilation (MV)'; (b) heat map illustrating the average ventilation rates achieved for 'natural ventilation only' for each zone.

The heat map in Figure 6b indicates that the south-easterly side of the building was much better ventilated, giving an insight into the airflow pattern across this subset of zones. This could be useful in informing healthcare professionals of the best zones in which to place an infectious individual, or which zones may be in greatest need of additional intervention.

Open bay scenario

To fully assess the capabilities of natural ventilation alone, a final scenario was considered where all windows and doors were fully open for the duration of the simulation. This aimed to mimic a 'Nightingale-style' hospital ward, which is fully open.

The exposure probability distribution (Figure 7a) shows RI = 0.0505, which is one of the lowest values across any of the scenarios. The heat map (Figure 7b) is almost identical to the scenarios with open windows and mechanical ventilation. When natural ventilation is used on a ward with open bays, allowing for crossflow across the whole building, it can be an effective tool. The simulations predicted up to 48 ACH average ventilation rates in particular zones in the ward, which is comparable to measurements in Peru [10] and Hong Kong [11]. However, in practical terms, when window openings are restricted for safety and thermal comfort, and doors are installed and closed for privacy or infection prevention and control, natural ventilation rates are reduced significantly.

Discussion

These simulation results illustrate the effects of weather conditions, building design and behavioural factors on airborne transmission when relying on natural ventilation. The initial scenario with natural ventilation alone illustrates how weather conditions can vary the risk of infection. The highest quanta concentrations happen infrequently (Figure 3), but may be important for the transmission of infection. Other key factors will include the presence, type and transmissibility of infection. However, the models represent a worst-case scenario, which show that when a set of conditions come together, such as the sustained presence of a more infectious individual combined with particular weather conditions, the chances of an outbreak become more likely.

The positive benefits of mechanical ventilation are well established and illustrated in the model when 3 ACH and 6 ACH are added to the natural ventilation. Despite 3 ACH of mechanical ventilation being half that of the UK recommended rate, it still dominated over natural ventilation, and dampened the effects of external weather conditions, reducing risk and uncertainty in both scenarios (>85% reduction in RI value). The addition of 6 ACH led to a further 11% reduction in the RI value. Thus, 3 ACH delivers the majority of the reduction, suggesting that even an underspecified mechanical ventilation system will provide better dilution and consistency as opposed to not acting at all. Whilst the application of air cleaners was not explicitly modelled, a similar result would likely be obtained.

This study demonstrated that poor ventilation rates are likely to be achieved when relying on natural ventilation alone, due, in part, to the internal design of hospitals and limited access to the ambient environment. Buildings contain many internal zones which do not have windows, leakage or vents to outside air; unless other mitigations are put in place, these locations may have no ventilation at all. Many hospitals designed with open bays have had doors added for patient privacy, and in older buildings, existing windows or outlets have more recently been reduced in size due to safety measures, or removed completely in an effort to improve energy efficiency [9]. Despite the original hospital design being able to provide sufficient ventilation, it is now likely that over time, many of these conditions are no longer met. It is critical that internal airflow is considered as part of a retrofit, and where modifications restrict window openings or reduce flow paths, additional ventilation should be considered to compensate.

This model has potential to identify dominant airflow patterns, and locations around the hospital which may alter ventilation and susceptibility to airborne infection. For example, in Figure 6b, zones on the south-easterly side of the building displayed higher ventilation rates than those on the north-westerly side, suggesting that air flows in a south-easterly

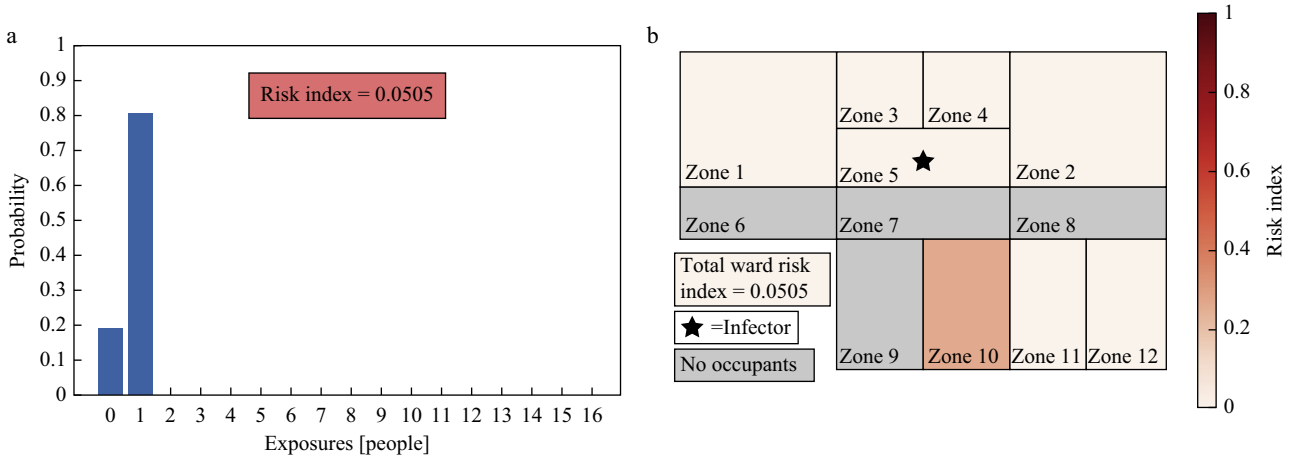

Figure 7. Predicted exposures for the 'open bay' scenario. (a) Probability distribution showing the weekly predicted exposures across the whole ward; (b) heat map showing the zonal risk index value based on predicted exposure.

direction. Additionally, in every scenario, the RI in Zone 10 was consistently higher, suggesting that this zone was susceptible to a dominant flow path carrying pathogens from the infector in Zone 5. It is possible that internal airflow rates governed by natural ventilation have a large impact on pathogen transport to these zones, but the zone ventilation rate is not efficient, nor fast enough for the removal of infectious material. This further supports the use of mechanical ventilation, or alternative approaches such as air cleaners, contrary to relying solely on natural methods.

As this study is based on a model, it has a number of limitations. The model is based on the floor plan, occupancy, windows and representative weather conditions for a single UK respiratory ward. However, the model does not aim to quantify risks explicitly on that ward. The scenarios were designed to be realistic, but only considered the influence of ventilation and not the complexities that exist in a real ward. The model is idealised and does not fully capture all the factors that create internal flows, including turbulent mixing, which is not present in the CONTAM airflow model, and variations in internal temperatures. However, the comparison of the airflow with CO_2 data suggests that the mixing achieved is realistic.

The use of a local transient weather file [45], using real historical data, enabled the modelling of possible scenarios. As with any transmission model, validation against infection cases is almost impossible, as identifying where the source of an outbreak originated, and replicating the exact transient behaviours, occupancy and external conditions at the time is difficult. The limitations of transmission models are discussed in Edwards *et al.* [15]. The choice of the infectiousness of an individual will adjust the RI values in these scenarios. For example, in the first scenario with natural ventilation alone, simulations with a pathogen emission rate of $q = 1$ quanta/h and $q = 10$ quanta/h result in RI values of 0.0337 and 0.2644, respectively. However, this does not alter the relative risk in each space, nor the overall spatial behaviour of pathogen transport to interconnected zones. In this study, the same infectiousness of $q = 0.5$ quanta/min ($q = 30$ quanta/h) was used as in previous work [15,16]. This is a realistic choice given that Mikszewski *et al.* [47] presented ranges of 15—4213 quanta/h for SARS-CoV-2, 18—8640 quanta/h for measles virus and 0.11—79 quanta/h for influenza virus. It was not the intention of the present study to predict exact outbreak patterns; rather, by using the modelling approach, the authors were able to develop a much better understanding of the long-term effects of natural ventilation and weather conditions on airflow and the potential for an outbreak.

The heat map illustrating the zonal RI could be used to help healthcare professionals identify areas of high risk, and to translate the complex modelling and mathematical assessment more easily into usable features for healthcare systems. This could be particularly useful in distinguishing between the ward or zone which requires intervention. In the scenario of a pandemic where the hospital is under elevated pressure with a scarcity of resources such as personal protective equipment (PPE), the heat map could help to assess whether the ward as a whole is high risk or whether it is only particular zones. For example, in Figure 4b, there are numerous zones with elevated risk and so it may be easier to apply a blanket mitigation of PPE to the whole ward. Whereas in Figure 5b, only Zone 10 has increased risk so here it could be more appropriate to only apply PPE to the visitors to this particular zone. Although this study did not investigate the implementation of outputs (e.g. heat maps) into healthcare systems directly, this accessibility and comprehensible illustration of the results is a priority.

In conclusion, through the use of transient weather conditions within an airflow and transmission model, this study highlighted how weather conditions have a significant influence on internal airflow, and can lead to uncertainty and periods of higher pathogen concentrations within ward environments. When these conditions are combined with the presence of a more infectious person on the ward, the probability of a large outbreak increases. This uncertainty also extends to ventilation rates, with many naturally ventilated spaces falling far below the recommended standard. Reliance on closed internal doors and restricted window openings is not likely to provide sufficient ventilation for wards based on the recommendation of 6 ACH provided in the guidance [5].

Mechanical ventilation or other similar approaches, such as the use of air cleaners, can help to reduce the effects of transient weather on natural ventilation. This includes ensuring a more consistent in-room ventilation rate, and reducing the unwanted transfer of air between spaces, and can, in turn, decrease the risk to patients. Through illustrative outputs such as heat maps, the authors hope to be able to advise engineering and healthcare professionals of the risk distribution of their multi-room hospital wards, and help make informed choices of mitigation strategies; this will be explored in future work.

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Author contributions

AJE: writing — review and editing, writing — original draft, visualization, validation, software, resources, project administration, methodology, investigation, funding acquisition, formal analysis, data curation, conceptualization. M-FK: writing — review and editing, conceptualization, funding acquisition, supervision. ML-G: writing — review and editing, conceptualization, funding acquisition, supervision. DP: writing — review and editing, conceptualization, funding acquisition, supervision. CJN: project administration, writing — review and editing, conceptualization, funding acquisition, supervision. Compliance with ethical standards.

Conflict of interest statement

During the COVID-19 pandemic, CJN was a participant in the UK Scientific Advisory Group for Emergencies (SAGE), and co-chaired the SAGE Environment and Modelling Sub-Group. The other authors have no competing interests to declare that are relevant to the content of this article.

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Data accessibility

The code and data are available at https://github.com/scaje/Contam_study_AJE.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhin.2024.02.017.

References

[1] Wang CC, Prather KA, Sznitman J, Jimenez JL, Lakdawala SS, Tufekci Z, et al. Airborne transmission of respiratory viruses. Science 2021;373:eabd9149.

[2] Bourouiba L. The fluid dynamics of disease transmission. Ann Rev Fluid Mech 2021;53:473—508.

[3] Li Y, Leung GM, Tang J, Yang X, Chao C, Lin JZ, et al. Role of ventilation in airborne transmission of infectious agents in the built environment-a multidisciplinary systematic review. Indoor Air 2007;17:2—18.

[4] NHS England. Respiratory disease. London: NHS England; 2022. Available at: https://www.england.nhs.uk/ourwork/clinical-policy/respiratory-disease/ [last accessed September 2021].

[5] NHS England. HTM03-01 Specialised ventilation for healthcare buildings. London: NHS England; 2021. Available at: https://www.england.nhs.uk/publication/specialised-ventilation-for-healthcare-buildings/.

[6] Park S, Choi Y, Song D, Kim EK. Natural ventilation strategy and related issues to prevent coronavirus disease 2019 (COVID-19) airborne transmission in a school building. Sci Total Environ 2021;789:147764.

[7] Linden PF. The fluid mechanics of natural ventilation. Ann Rev Fluid Mech 1999;31:201—38.

[8] Mao J, Gao N. The airborne transmission of infection between flats in high-rise residential buildings: a review. Build Environ 2015;94:516—31.

[9] Gilkeson C, Camargo-Valero M, Pickin L, Noakes CJ. Measurement of ventilation and airborne infection risk in large naturally ventilated hospital wards. Build Environ 2013;65:35—48.

[10] Escombe AR, Oeser CC, Gilman RH, Navincopa M, Ticona E, Pan W, et al. Natural ventilation for the prevention of airborne contagion. PLoS Med 2007;4:e68.

[11] Qian H, Li Y, Seto W, Ching P, Ching W, Sun H. Natural ventilation for reducing airborne infection in hospitals. Build Environ 2010;45:559—65.

[12] Stensballe LG, Devasundaram JK, Simoes EA. Respiratory syncytial virus epidemics: the ups and downs of a seasonal virus. Pediatr Infect Dis J 2003;22:S21—32.

[13] Pica N, Bouvier NM. Environmental factors affecting the transmission of respiratory viruses. Curr Opin Virol 2012;2:90—5.

[14] Leprince V, Carrie FR. Comparative analysis of window airing models proposed in prEN 16798-7 and influence of internal resistances. Proceedings of CLIMA, 22—25 May 2016, Aalborg, Denmark.

[15] Edwards AJ, Benson L, Guo Z, López-García M, Noakes CJ, Peckham D, et al. A mathematical model for assessing transient airborne infection risks in a multi-zone hospital ward. Build Environ 2023;238:110344.

[16] Noakes CJ, Sleigh PA. Mathematical models for assessing the role of airflow on the risk of airborne infection in hospital wards. J R Soc Interface 2009;6:S791—800.

[17] López-García M, King MF, Noakes CJ. A multicompartment SIS stochastic model with zonal ventilation for the spread of nosocomial infections: detection, outbreak management, and infection control. Risk Anal 2019;39:1825—42.

[18] Hodgson AT, Nabinger SJ, Persily AK. Volatile organic compound concentrations and emission rates measured over one year in a new manufactured house. Berkeley, CA: Lawrence Berkeley National Lab; 2004. Available at: https://www.osti.gov/servlets/purl/838617.

[19] Guyot G, Sayah S, Guernouti S, Mélois A. Role of ventilation on the transmission of viruses in buildings, from a single zone to a multizone approach. Indoor Air 2022;32:e13097.

[20] Jung J, Lee J, Jo S, Bae S, Kim JY, Cha HH, et al. Nosocomial outbreak of COVID-19 in a hematologic ward. Infect Chemother 2021;53:332—41.

[21] UK Scientific Advisory Group for Emergencies. Emg/transmission group/spi-b: COVID-19 transmission in hotels and managed quarantine facilities (MQFS). London: SAGE; 2021. Available at: https://www.gov.uk/government/publications/emg-covid-19-transmission-in-hotels-and-managed-quarantine-facilities-mqfs-9-september-2021.

[22] Dols W, Polidoro B. CONTAM user guide and program documentation version 3.4, technical note. Gaithersburg, MD: National Institute of Standards and Technology; 2020.

[23] National Institute of Standards and Technology. Nist CONTAM. Gaithersburg, MD: NIST; 2022. Available at: https://www.nist.gov/services-resources/software/contam [last accessed May 2022].

[24] Yang W, Gao N. The transport of gaseous pollutants due to stack effect in high-rise residential buildings. Int J Ventil 2015;14:191—208.

[25] Mao J, Yang W, Gao N. The transport of gaseous pollutants due to stack and wind effect in high-rise residential buildings. Build Environ 2015;94:543—57.

[26] Reichman R, Dubowski Y. Gaseous pollutant transport from an underground parking garage in a Mediterranean multi-story building — effect of temporal resolution under varying weather conditions. Build Simul 2021;14:1511—23.

[27] Parker ST, Lorenzetti DM, Sohn MD. Implementing state-space methods for multizone contaminant transport. Build Environ 2014;71:131—9.

[28] Cheong CH, Park B, Lee S. Design method to prevent airborne infection in an emergency department. J Asian Architect Build Eng 2018;17:581—8.

[29] Shrestha P, DeGraw JW, Zhang M, Liu X. Multizonal modeling of SARS-CoV-2 aerosol dispersion in a virtual office building. Build Environ 2021;206:108347.

[30] Yan S, Wang LL, Birnkrant MJ, Zhai J, Miller SL. Evaluating SARS-CoV-2 airborne quanta transmission and exposure risk in a mechanically ventilated multizone office building. Build Environ 2022;219:109184.

[31] Li T, Yang Z, Di B, Wang M. Hand-foot-and-mouth disease and weather factors in Guangzhou, southern China. Epidemiol Infect 2014;142:1741—50.

[32] Sadys M. Effects of wind speed and direction on monthly fluctuations of *Cladosporium conidia* concentration in the air. Aerobiologia 2017;33:445—56.

[33] Dbouk T, Drikakis D. Weather impact on airborne coronavirus survival. Phys Fluids 2020;32:093312.

[34] Dbouk T, Drikakis D. Fluid dynamics and epidemiology: seasonality and transmission dynamics. Phys Fluids 2021;33:021901.

[35] Dbouk T, Drikakis D. The computational fluid dynamics-based epidemic model and the pandemic scenarios. Phys Fluids 2022;34:027104.

[36] Pani SK, Lin NH, RavindraBabu S. Association of COVID-19 pandemic with meteorological parameters over Singapore. Sci Total Environ 2020;740:140112.

[37] Habeebullah TM, Abd El-Rahim IH, Morsy EA. Impact of outdoor and indoor meteorological conditions on the COVID-19 transmission in the western region of Saudi Arabia. J Environ Manag 2021;288:112392.

[38] Das SK, Alam JE, Plumari S, Greco V. Airborne virus transmission under different weather conditions. AIP Adv 2022;12:015019.

[39] Emmerich SJ, Heinzerling D, Choi JI, Persily AK. Multizone modeling of strategies to reduce the spread of airborne infectious agents in healthcare facilities. Build Environ 2013;60:105—15.
[40] García-Tobar J. A comparative study of indoor radon levels between two similar dwellings using CONTAM software. Environments 2018;5:59.
[41] Myatt TA, Kaufman MH, Allen JG, MacIntosh SL, Fabian MP, McDevitt JJ. Modeling the airborne survival of influenza virus in a residential setting: the impacts of home humidification. Environ Health 2010;9:1—7.
[42] García-Tobar J. Weather-dependent modelling of the indoor radon concentration in two dwellings using CONTAM. Indoor Built Environ 2019;28:1341—9.
[43] Zhu S, Jenkins S, Addo K, Heidarinejad M, Romo AS, Layne A, et al. Ventilation and laboratory confirmed acute respiratory infection (ARI) rates in college residence halls in College Park, Maryland. Environ Int 2020;137:105537.
[44] Rudnick S, Milton D. Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. Indoor Air 2003;13:237—45.
[45] Climate.OneBuilding. Climate data. Climate.OneBuilding; 2022. Available at: https://climate.onebuilding.org/WMO_Region_6_Europe/GBR_United_Kingdom/index.html [last accessed September 2022].
[46] Persily A, de Jonge L. Carbon dioxide generation rates for building occupants. Indoor Air 2017;27:868—79.
[47] Mikszewski A, Stabile L, Buonanno G, Morawska L. The airborne contagiousness of respiratory viruses: a comparative analysis and implications for mitigation. Geosci Front 2022;13:101285.

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Modelling the transmission of airborne infections in enclosed spaces

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SUMMARY

The Wells–Riley equation for modelling airborne infection in indoor environments is incorporated into an SEIR epidemic model with a short incubation period to simulate the transmission dynamics of airborne infectious diseases in ventilated rooms. The model enables the effect of environmental factors such as the ventilation rate and the room occupancy to be examined, and allows the long-term impact of infection control measures to be assessed. A theoretical parametric study is carried out to demonstrate how changes to both the physical environment and infection control procedures may potentially limit the spread of short-incubation-period airborne infections in indoor environments such as hospitals.

INTRODUCTION

The indoor air in buildings can play a significant role in the transmission of a wide range of infections. Aerosolized infectious agents may be introduced to the air by room occupants through actions such as coughing, sneezing and, in some instances – such as norovirus infection – vomiting. These microorganism-bearing droplets evaporate rapidly to form droplet nuclei, which with a typical diameter of $<5\,\mu$m, can remain suspended in air for many hours. Ventilation systems and convection currents within rooms can disperse droplet nuclei over a wide area, with the potential to infect other occupants.

Infections that are known to be transmitted primarily by an airborne route include viral diseases such as measles and influenza and bacterial infections such as tuberculosis. In some emerging infections, for example those caused by the human metapneumovirus and the SARS-associated coronavirus the airborne route of transmission is also thought to be important. In addition to these communicable diseases there is increasing evidence that airborne transmission may play a role in the dissemination of many opportunistic pathogens responsible for a range nosocomially acquired infections. In particular airborne transmission has been implicated in nosocomial outbreaks of *Staphylococcus aureus*, including methicillin-resistant strains (MRSA) [1–3], *Acinetobacter* spp. [4, 5] and *Serratia marcescens* [6]. It is also thought that the high attack rates during norovirus outbreaks may be due to dispersion via aerosols [7]. It has been estimated that 10–20% of all nosocomial infections are spread by this route [8] which equates to a cost to the National Health Service in England in excess of £100 million annually [9].

These concerns together with the more recent threat of bioterroism attacks involving the deliberate release

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of an airborne infectious agent [10, 11] have prompted a resurgence of interest in measures to control airborne pathogens. Methods that have recently been discussed by researchers in the area include improving mechanical ventilation [12], use of personal protective equipment [13] and the use of ultraviolet germicidal irradiation (UVGI) devices both within rooms [14, 15] and in air-conditioning ducts [16]. For example experimental investigations have shown that the introduction of UVGI lamps reduces the levels of infectious material present in the air [17, 18]. Field trials [14, 16] have also yielded results suggesting that UVGI systems may have a beneficial impact.

Despite this interest, little work has been done to evaluate the overall benefits, particularly in developing epidemiological models that could be used to assess the long-term impacts of introducing new interventions. Models for examining infection in confined spaces are generally based on the work of Wells [19] and Riley *et al.* [20], and are limited to describing only the number of new infections for a fixed number of infectors not the full dynamics of an epidemic. Riley *et al.* did apply their model to a measles outbreak, but used discrete time steps based on the incubation period to approximate subsequent generations of infectors. We have presented a first step to addressing this limitation by combining ventilation-based models of indoor airborne transmission [13, 20] with classical SIR epidemic models [21, 22] that include an incubation period. The resulting systems of equations are used in a theoretical study to model the dynamics of an airborne infection in an environment such as a hospital. Through this parametric study it is demonstrated how a range of infection control measures may influence airborne disease transmission in enclosed environments.

SIR MODELS FOR A SHORT INCUBATION PERIOD DISEASE IN A VENTILATED SPACE

Epidemiological models for general disease transmission in populations have been used for many years and are well documented [21, 23]. The most common deterministic models are known as SIS and SIR models, and consist of systems of first-order differential equations describing the progression from susceptible (S) to infectious (I) individual. In an SIS model it is assumed that on recovery the individual becomes a susceptible again, whereas the SIR model considers that infectious people are removed from the transmission process either by death or isolation, or recovery to an immune state. The transfer between states in both models is governed by rate constants that are estimated from epidemiological data. These basic models have been used by numerous researchers and extended to include factors such as incubation periods, vaccination and immunity and interaction between different populations [21, 23]. They have also been applied to the spread of many diseases including tuberculosis [24] and the impact of HIV/AIDS on tuberculosis [25].

Many infectious diseases such as those caused by norovirus and influenza viruses that are problematic in institutions such as hospitals and nursing homes occur as distinct outbreaks over a relatively short timescale. For example the incubation period for influenza is typically 1–3 days and patients may then be infectious for a period of 4–6 days [26]. Norovirus, a major cause of gastroenteritis in hospitals throughout the world [7] that regularly leads to ward closures and staffing shortages [27] has a similar incubation period (1–2 days), however, the patient is usually only highly infectious for around 2 days [28]. The short incubation and infectious periods of these diseases are considered to be small enough that the population dynamics (admission and discharge rates) do not have to be included in a model. It is also assumed that people who become infected with, say, influenza, are not susceptible to re-infection on recovery (within the timescale of the model) and, therefore, an SIR type model is appropriate.

Basic SIR model

The classic deterministic SIR model, based on the work of Kermack & McKendrick [22], is given by three ordinary differential equations linking the change in number of susceptibles, S, the number of infectors, I, and the number removed through death, isolation or recovery to an immune state, R

$$\frac{\mathrm{dS}}{\mathrm{d}t} = -\beta \mathrm{SI}, \tag{1}$$

$$\frac{\mathrm{dI}}{\mathrm{d}t} = \beta \mathrm{SI} - \gamma \mathrm{I}, \tag{2}$$

$$\frac{\mathrm{dR}}{\mathrm{d}t} = \gamma \mathrm{I}, \tag{3}$$

$$\mathrm{S} + \mathrm{I} + \mathrm{R} = N, \tag{4}$$

Here N is the total population size, β is the contact rate between susceptibles and infectors, and γ is the

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removal or recovery rate. By non-dimensionalizing the variables as

$$u=\frac{\mathrm{S}}{N},\quad v=\frac{\mathrm{I}}{N},\quad w=\frac{\mathrm{R}}{N},\quad \tau=\gamma t,\quad R_0=\frac{\beta N}{\gamma}, \tag{5}$$

the model can be re-written as

$$\frac{\mathrm{d}u}{\mathrm{d}\tau}=-R_0uv,\quad \frac{\mathrm{d}v}{\mathrm{d}\tau}=(R_0u-1)v,\quad \frac{\mathrm{d}w}{\mathrm{d}\tau}=v, \tag{6}$$

R_0 is known as the basic reproductive ratio and describes the average number of new cases that an infector produces in a particular population. When $R_0<1$ the disease dies out, while $R_0>1$ indicates that the infection rate is greater than the removal rate which may potentially lead to an epidemic.

Effect of the environment

Mathematical models examining airborne infection in confined spaces were first considered by Wells [19]. He introduced a unit of infection termed a 'quantum', defined as the amount of infectious material to infect $1-(1/\mathrm{e})$ (i.e. 63·2%) of the people in an enclosed space. Despite its stochastic definition, the number of quanta in a room is generally considered to be a physical measure of the infectious material present, which effectively indicates both the quantity and pathogenicity of an infectious material present in the air as well as the average susceptibility of a susceptible person. Wells published equations based on the quanta unit which showed a dependence of the number of new cases on the size of the space as well as the number of infectors, I, and susceptibles, S. Riley *et al.* [20] modified this model, to give an expression known as the Wells–Riley equation, reflecting the exponential increase in the number of new cases, C, with time for steady-state quanta levels in a room space.

$$C=\mathrm{S}(1-\mathrm{e}^{-(\mathrm{I}pqt/AV)}). \tag{7}$$

Here, A is the ventilation rate in air changes per hour (AC/h), V is the room volume (m³), p is the average pulmonary ventilation rate of the susceptibles (m³/h) and q is the quanta production rate per infector (quanta/h). A further modification was introduced by Gammaitoni & Nucci [29] who published expressions linking the rate of infection with the room ventilation rate for non-steady state cases. They then used these expressions [13] to assess risks in clinical procedures where the room was initially considered to be clean. A review of the above models by Beggs *et al.* [30] demonstrated their range of applicability and used Gammaitoni & Nucci's general equation to evaluate the effects of room size, occupancy and ventilation conditions on the number of new infections.

The effect of the indoor environment can be examined by considering Gammaitoni & Nucci's [13, 29] equations relating the rate of infections in a ventilated space with a volume V (m³), and a ventilation rate of A (AC/h).

$$\frac{\mathrm{dS}}{\mathrm{d}t}=\frac{-p}{V}Q\mathrm{S}, \tag{8}$$

$$\frac{\mathrm{d}Q}{\mathrm{d}t}=-AQ+q\mathrm{I}, \tag{9}$$

In this case Q is the total quanta level in the space. Assuming continuous generation of quanta by the infectors and steady-state ventilation ($\mathrm{d}Q/\mathrm{d}t=0$), the level of quanta in the space is given by

$$Q=\frac{q\mathrm{I}}{A} \tag{10}$$

and equation (8) becomes

$$\frac{\mathrm{dS}}{\mathrm{d}t}=\frac{-pq}{VA}\mathrm{IS}. \tag{11}$$

This rate of reduction of susceptibles in equation (11) as a result of new infections is in fact equivalent to the rate of increase in new cases given by the derivative of the Wells–Riley equation [equation (7)] with time.

Comparing equation (11) with equation (1) we see that the term (pq/VA) is equivalent to β in the basic SIR model. Therefore the two models can be combined to give the following expressions.

$$\frac{\mathrm{dS}}{\mathrm{d}t}=-\frac{pq}{VA}\mathrm{IS}, \tag{12}$$

$$\frac{\mathrm{dI}}{\mathrm{d}t}=\frac{pq}{VA}\mathrm{IS}-\gamma\mathrm{I}, \tag{13}$$

$$\frac{\mathrm{dR}}{\mathrm{d}t}=\gamma\mathrm{I}. \tag{14}$$

This model can also be represented by the dimensionless equations above but with the basic reproductive ratio now defined by

$$R_0=\frac{pq}{VA}\frac{N}{\gamma}. \tag{15}$$

The model combines the effect of the physical environment with equations describing the progression of the disease and provides a means of quantifying the contact rate in terms of the room ventilation,

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environmental conditions and level of airborne infectious material in the space. The definition of R_0 in these terms enables the effect of ventilation and room parameters on the disease transmission to be compared for different cases.

Inclusion of a short incubation period

Although the above model can give some useful indications about airborne disease transmission and the influence of physical parameters, it is difficult to apply to real situations as most diseases have an incubation period before the infected person becomes infectious to others. This limitation can be addressed by extending the SIR model for a ventilated room [equations (12)–(14)] to include an incubation period by assuming the susceptible is initially transferred to an exposed state, E, before going on to become an infector. The model is now referred to as an SEIR model, and the description becomes

$$\frac{\mathrm{dS}}{\mathrm{d}t} = -\frac{pq}{VA}\mathrm{IS}, \tag{16}$$

$$\frac{\mathrm{dE}}{\mathrm{d}t} = \frac{pq}{VA}\mathrm{IS} - \alpha\mathrm{E}, \tag{17}$$

$$\frac{\mathrm{dI}}{\mathrm{d}t} = \alpha\mathrm{E} - \gamma\mathrm{I}, \tag{18}$$

$$\frac{\mathrm{dR}}{\mathrm{d}t} = \gamma\mathrm{I}, \tag{19}$$

$$\mathrm{S} + \mathrm{I} + \mathrm{E} + \mathrm{R} = N, \tag{20}$$

where α is the progression rate from exposed to infector, equivalent to the reciprocal of the incubation period.

As previously this model can be re-written in terms of non-dimensional variables

$$\left.\begin{array}{llll} u = \dfrac{\mathrm{S}}{N}, & x = \dfrac{\mathrm{E}}{N}, & v = \dfrac{\mathrm{I}}{N}, & \\ w = \dfrac{\mathrm{R}}{N}, & \tau = \gamma t, & \sigma = \dfrac{\alpha}{\gamma}, & \end{array}\right\} \tag{21}$$

to give

$$\left.\begin{array}{ll} \dfrac{\mathrm{d}u}{\mathrm{d}\tau} = -R_0 uv, & \dfrac{\mathrm{d}x}{\mathrm{d}\tau} = R_0 uv - \sigma x, \\ \dfrac{\mathrm{d}v}{\mathrm{d}\tau} = \sigma x - v, & \dfrac{\mathrm{d}w}{\mathrm{d}\tau} = v. \end{array}\right\} \tag{22}$$

The reproductive ratio remains unchanged from equation (15) as the total number of new infections depends on the rate at which an infector produces new cases with respect to the removal rate, which is not affected by a delay in a susceptible person becoming infective.

BEHAVIOUR OF SHORT INCUBATION PERIOD SEIR MODEL

The SEIR model described above [equations (16)–(19)] can be used in a theoretical study to examine how changes in the ward environment may influence outbreaks of short-incubation-period diseases. As the models are systems of nonlinear differential equations, solutions are most easily found using numerical methods. In this study the mathematical analysis package Maple v.9 (MaplesoFt, Waterloo, Canada) is used to numerically solve the governing equations and produce typical epidemic curves showing the probable disease progression with time.

Choice of parameters

The study was based on the initial conditions and parameter ranges given in the Table.

The numbers of people are intended to be representative of an area of a hospital with, say, 100 patients on a number of connected wards and 100 health-care workers/other people. Each patient is assumed to occupy a volume of 36 m³ ($3 \times 4 \times 3$ m), with the remainder of the area (corridors, offices, nurses' rooms, treatment rooms, etc.) occupying the same space again giving a total volume of 7200 m³. A pulmonary ventilation rate of 8 l/min is typical for an adult [31]. The model assumes the population is constant during the outbreak and that the air in the wards is fully mixed. Although the population may not be constant in some situations, in others, such as norovirus outbreaks, wards are usually closed to new admissions and discharges are postponed, therefore, this assumption is reasonable under these circumstances. Likewise the assumption that the air is fully mixed may not be appropriate for all situations. However, both these assumptions enable a first approximation to be made about the transmission dynamics of airborne infection in an enclosed area, and further possible improvements are outlined in the discussion. The values for α and γ are based on data for the incubation time and periods of infectivity for influenza and norovirus as given above.

The value for the quanta production rate, q, in any disease outbreak is the parameter that is the most

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Table. *Basic conditions and study parameter ranges for SIR model simulations*

Parameter	Base value	Study range
S (at $t=0$)	199	99–199
I (at $t=0$)	1	1
E (at $t=0$)	0	0
R (at $t=0$)	0	0
A	3 AC/h	3–8 AC/h
q	10 quanta/h	1–50 quanta/h
V	7200 m^3	7200 m^3
p	0·48 m^3/h (8 l/min)	0·06–0·48 m^3/h
α	1/day (1-day incubation period)	1–0·33/day (1- to 3-day incubation period)
γ	0·5/day (2-day infectious period)	0·5–0·166/day (2- to 6-day infectious period)

difficult to quantify. To date, most of the quanta values presented in the literature relate to tuberculosis [12, 13] and very little data have been published relating to quanta production rates for short-incubation-period infections that may be more of an issue in a typical hospital environment. Rudnick & Milton [31] estimated values of quanta production rate for rhinovirus as 1–10 quanta/h and influenza as 15–128 quanta/h depending on the calculation method. Riley *et al*. [20] calculated a value of 570 quanta/h for a typical measles case, which is consistent with the high transmission rates of this disease in school outbreaks. For the purposes of this study, quanta production values of 1–50 quanta/h are used as suitable values to examine the behaviour of the model.

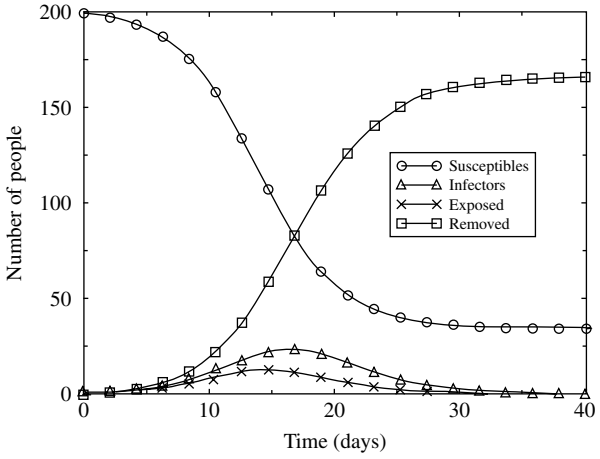

Fig. 1. Predicted dynamics of an outbreak of an airborne infection with the disease and environment characteristics given by the base parameters in the Table.

Dynamics of an outbreak

Figure 1 shows a typical result from the SEIR model for a theoretical airborne infection given by the base parameters in the Table. The epidemic curves produced are characteristic of those produced by all SEIR models. Initially the number of susceptibles falls with time, with the numbers of infectors, exposed and removals all increasing. The outbreak peaks after about 16 days, with around 25 active infectors, and the rate of change of both susceptibles and removals at a maximum. After this point the outbreak starts to wane, with all the variables levelling off to constant values. The outbreak is over after about 35 days, with approximately 20% of the susceptibles remaining uninfected. The curve indicating the exposed group is a similar shape to the infector profile over the period, but peaks 1 day (the incubation period) earlier at a lower value. R_0 for this particular case is 2·133, a value that is indicative of an epidemic.

Impact of physical environment

The model is first used to examine how changes to the physical environment, in particular the ventilation rate and the occupancy level, may affect the course of an outbreak of an airborne infection. Figures 2 and 3 show the effect of increasing the ventilation rate on the course of the outbreak modelled in Figure 1. In Figure 2 the ventilation rate is increased to 5 AC/h. This has the effect of increasing the duration of the outbreak, yet it reduces the total number of cases. The reproductive number is now $R_0=1·28$, reflecting

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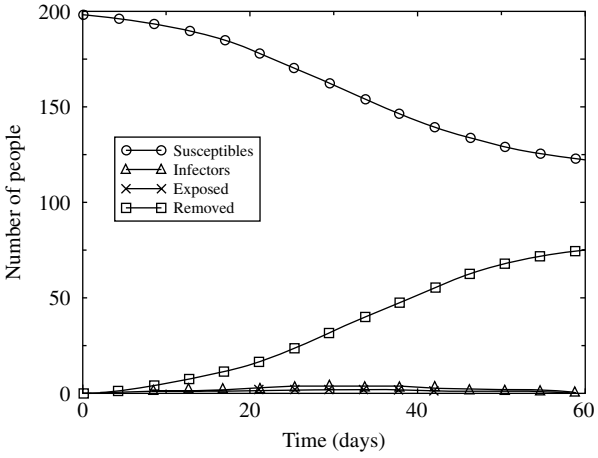

Fig. 2. Predicted progression of the epidemic modelled in Figure 1, with the ventilation rate increased to 5 AC/h.

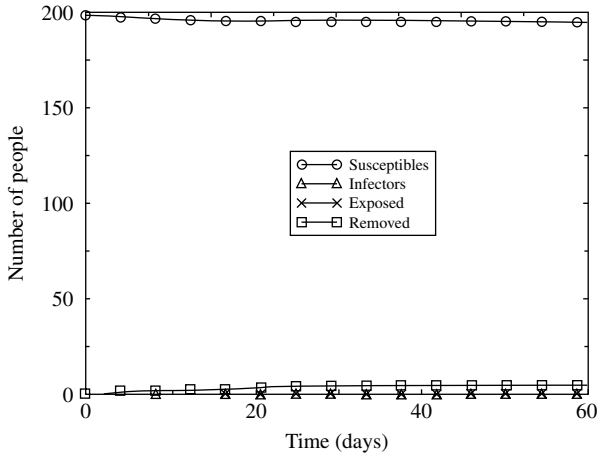

Fig. 3. Predicted progression of the epidemic modelled in Figure 1, with the ventilation rate increased to 8 AC/h.

the lower transmission rate for the disease. The rate of infection is much slower and the peak number of infectors significantly lower.

In Figure 3 the ventilation rate is 8 AC/h, which has a dramatic effect on the dynamics of the outbreak with less than 10% of the susceptibles infected. This phenomenon is always seen with SIR-type models when the contact rate is smaller than the removal rate ($R_0 = 0{\cdot}799$), effectively meaning the infectors recover before they have the chance to infect anyone else.

The impact of the ventilation rate can also be examined by considering the reproductive number, R_0. Figure 4 shows how R_0 changes with the ventilation rate, again for the base parameters in the Table, and also with an occupancy of 50%. It can be seen that with 200 occupants (S = 199, I = 1), a ventilation rate below 6·4 AC/h results in a value of $R_0 > 1$ and the potential for this infection to become an epidemic. With only 100 occupants (S = 99, I = 1), a ventilation rate of half this value will lead to the same conditions.

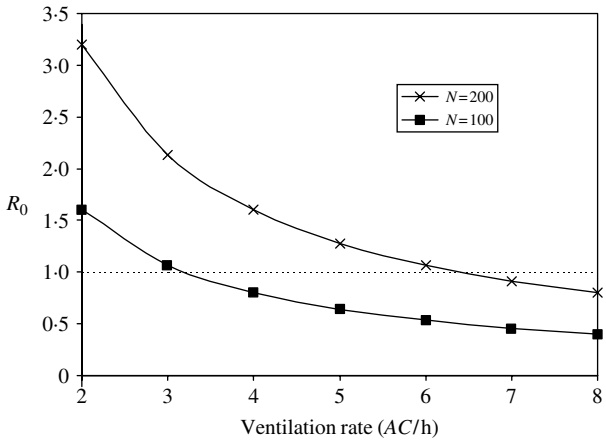

Fig. 4. Impact of ventilation and ward occupancy on the potential for an epidemic, for the base conditions in the Table.

Impact of disease and infector/susceptible characteristics

Further examination of the model can reveal how the characteristics of the infection and the infectors and susceptibles may affect the progression of an outbreak of an airborne infection. Increasing the incubation period of an infection has the result of increasing the duration of the outbreak, but it does not impact on the overall number of people infected, and the reproductive number remains unchanged. However, this may have implications for infection control procedures as outlined in the Discussion section.

The influence of both the disease itself and the infector and susceptible characteristics can be examined by considering the recovery rate, γ, the pulmonary ventilation rate, p, and the quanta production rate, q, which incorporates the infectivity of the pathogen, the response of the average susceptible and the ability of the average infector to disseminate the infection into the room in an airborne state. It can be seen from equation (15) that R_0 is directly proportional to both the infectious period ($1/\gamma$) and the quanta production rate. Hence, as expected, infections characterized by a low quanta production rate require a much longer infectious period for an outbreak to reach epidemic levels ($R_0 > 1$) than those infections with a high quanta production rate.

The relationship between R_0 and quanta production rate for three pulmonary ventilation rates

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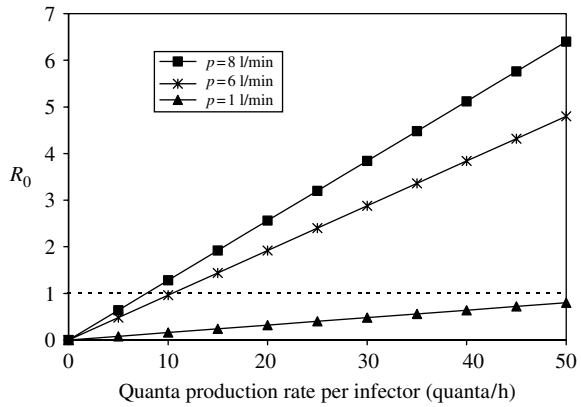

Fig. 5. Effect of quanta production rate on reproductive number at different pulmonary ventilation rate.

is also linear as demonstrated by Figure 5. A value of $p=8$ l/min is typical of a normal adult, while $p=6$ l/min is intended to be representative of a child. In both of these cases the reproductive number is directly proportional to the quanta production rate and exceeds $R_0=1$ when $q=8$–10 quanta/h indicating the possibility of an epidemic. However, when the value of p is reduced to 1 l/min even at high quanta production rates the reproductive number does not exceed $R_0=1$.

DISCUSSION

The models and results outlined in this study have been used to demonstrate the probable dynamics of airborne infections and the impacts of changes in the physical environment or disease characteristics. However, these results can also be interpreted in the context of infection control measures. The results presented in Figures 2 and 3 suggest that increasing the ventilation rate may reduce the rate of infection and that high ventilation rates may remove the potential for an epidemic altogether. In a real situation it is likely that a moderate increase in ventilation rate may make an outbreak more manageable, with for example fewer problems with staffing shortages and a higher possibility of isolating the smaller numbers of infectors. Reducing the ward occupancy density was also shown to have a similar impact on infection rates, with the results in Figure 4 indicting that much lower ventilation rates were necessary to prevent an outbreak with only half the original number of occupants.

The effect of both the quanta production rate and the infectious period of the disease, also have implications for infection control procedures in the event of an outbreak. For infections that have relatively low quanta production rates, isolation of infectors may be an effective means of preventing an epidemic, particularly where the disease has a long infectious period. For example, using the base parameters in the Table where an infectious patient is emitting 10 quanta/h and the infectious period of the disease is 2 days, $R_0=2{\cdot}133$, suggesting an epidemic is likely to occur. If the patients are diagnosed and isolated within 1 day, the effective reduction in the infectious period results in $R_0<1$ and may prevent an epidemic. However, for highly contagious diseases, indicated by high quanta production rates, epidemic conditions may be present with an infectious period of less than 8 h. In these cases it may be impossible to isolate individual cases quickly enough and it may be necessary to isolate whole wards or units as seen in norovirus outbreaks [27].

The effects of incubation and infectious period described here are not unique to this model for airborne transmission, and are seen with all SIR models that incorporate an incubation period. However, they are still important to consider in the context of airborne infections, as it is likely that the transmission rate, $\beta=pq/VA$, will be different than for many infections transmitted via contact routes. The rate may also be less controllable as isolating patients with airborne infections is more involved than for those with infections that are only transmitted by contact, generally requiring the use of a negatively pressurized isolation room [32].

The final aspect of the parametric study is also relevant to infection control procedures. Although the pulmonary ventilation rate 1 l/min plotted in Figure 5 is an unrealistic breathing rate for a normal person, it may be equivalent to introducing some form of protection such as facemasks. In this case p can be considered to be the rate at which a person breathes only the contaminated air. Gammaitoni & Nucci [13] considered this intervention in their modelling and suggested that surgical and HEPA masks reduce the pulmonary ventilation of contaminated air to the equivalent of $0{\cdot}6p$ and $0{\cdot}03p$ respectively. A value of $p=1$ l/min in Figure 5 is 0·125 of the original value of 8 l/min for an adult, and is therefore representative of the level of reduction that the use of masks may achieve.

Although the results presented in this study are all for theoretical cases, they demonstrate how infection control interventions may reduce the number of

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infections, and possibly prevent an outbreak. The study has shown that the models can be used to examine a wide range of possible infection control measures, some of which require physical modifications such as changes to the ventilation system and others that are procedural such as isolation of patients or the use of face masks. This allows different controls to be compared and the most appropriate measures for the situation to be selected. The models may also be applied to evaluating further engineering infection control measures such as the application of upper room UVGI devices. The effectiveness of UVGI systems can be quantified in terms of an effective air change rate. For example Riley *et al*. [33] showed that the effectiveness of a 17 W UV fitting in their ventilated test room against airborne bacille Calmette–Guerin (BCG) was equivalent to an increase in the ventilation rate of 10 air changes per hour. The ability to make this comparison may be of benefit in situations where it is believed that increasing the ventilation rate will be beneficial, however, it is impractical or too expensive to fit a new air-conditioning system. In such cases the fitting of UV lamps could be a possible solution as they are easily installed in most buildings.

The model presented here does have a number of limitations. The equations are based on the assumption that the room air is fully mixed and, therefore, has a uniform distribution of quanta throughout the space. In reality most rooms are not well mixed and room air simulation results suggest that considerably higher infection concentrations will occur close to the source [30]. The risk of disease transmission is therefore likely to be greater for susceptibles in close proximity to the infectors. This was demonstrated by an outbreak of tuberculosis in an Arkansas hospital caused by aerosols generated by irrigation of a tuberculous abscess [34], where the prevalence of tuberculin reactivity decreased considerably with the distance from the source. Although increasing the ventilation rate in a space will in general reduce the bioburden in the air and hence the risk of infection for occupants, the design of ventilation systems may have a significant bearing on the actual distribution of bioaerosols in the space. For example previous computational and analytical studies [15, 35] have shown that the disinfection potential of devices such as UVGI is strongly related to the layout of the ventilation system, and a change in ventilation system design could have a negative impact on infection control.

The applicability of the model presented here is also limited by the assumption of a closed population and the deterministic nature of the equations. Although some populations may be assumed to have no inputs and outputs, particularly over short periods of time, the assumption is not strictly valid for many real hospital wards, especially where there are significant numbers of visitors and a high patient throughput. In these cases it is easily possible to extend the model to include admission and discharge rates, such as those used to simulate the transmission of tuberculosis [24]. For more complex situations it would also be possible to model the staff, patients and visitors as separate patient groups and include the interaction between them such as in Cooper *et al*. [36]. The issue of the deterministic nature of the model is significant in situations where the risk of infection may be influenced by chance events as much as by the environment, such as when the number of individuals involved in an outbreak is small. The deterministic model presented here will still give useful indicators in these cases, particularly when comparing infection control measures. However, it is possible to use similar assumptions to formulate stochastic SIR models [21, 23], which may be more appropriate for some cases.

When using this model, parameters such as the room size, room ventilation rate and pulmonary ventilation rate can all be calculated or estimated for a particular case with a reasonable level of confidence. However, determining a suitable value for the quanta is much more difficult. The fact that the concept of the quanta encompasses the infectivity and virulence of a given strain of a pathogenic microorganism, as well the susceptible and infector characteristics, means that even with the same infection there are likely to be wide variations in suitable values. It is also likely that in reality an infector will not remain at the same level of infectiousness throughout their illness, but will become less infectious as they start to recover. Most of the values quoted in the literature relate to tuberculosis outbreaks [12, 13] and are calculated by applying models such as equations (8) and (9) to actual cases to find an average value for the quanta. Values collated by Beggs *et al*. [30] for several tuberculosis outbreaks indicated the large range of quanta values that may be associated with a single disease. For example typical tuberculosis patients were seen to generate quanta levels of the order of 1·25 quanta/h, however, some cases were noticeably more infective, with quanta levels of up to

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60 quanta/h. However, these values were all much lower than the values calculated following outbreaks associated with a range of clinical procedures. Quanta values calculated by Gammaitoni & Nucci [13] included 360 quanta/h for a bronchoscopy-related outbreak [37] and 2280 quanta/h following a hip abscess irrigation [34], suggesting that some clinical procedures may create significant numbers of aerosolized microorganisms. For predicting the likelihood of epidemics for other airborne infections, where a suitable quanta value is not known, a similar calculation method to that used by Nardell *et al*. [12] can be used by applying the model to a previous outbreak and selecting a value of quanta such that the results approximate to the progression of the infection seen in reality. Alternatively predictions can be made at a range of quanta values to evaluate the impact of interventions for a range of cases.

Despite the limitations of the model, the predicted results suggest that changes in the physical environment may lead to a long-term reduction in infections and potentially prevent epidemics. This is in agreement with findings from several studies examining the impact of interventions such as UVGI lamps. For example Wells *et al*. [38] investigating the impact of UV air disinfection in schools over a 5-year period showed a consistently lower incidence of measles in the irradiated schools. Evidence is also given by Menzies *et al*. [16], who showed in a double-blind study that the incidence of a range of symptoms, including respiratory complaints, decreased following the introduction of UV air disinfection in the air-conditioning ducts of an office building. Hence the model described here will, therefore, at the very least give an indication of the impact of various factors in the physical environment.

CONCLUSIONS

The model developed in this study shows how environmental factors may be included in classical epidemic models to examine the impact of changes in the physical environment and disease characteristics on the transmission of airborne infection in ventilated rooms. The parametric study has shown that the model can be used to examine a range of infection control measures and the results suggest that the most suitable method depends on both the infection characteristics and the physical environment.

Although the model developed here is relatively simple, the same methodology could easily be applied to the more complex epidemic models in the literature, including stochastic models suitable for small populations [21] and the models for tuberculosis spread with factors such as HIV/AIDS [25].

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DECLARATION OF INTEREST

None.

REFERENCES

1. **Rutula WA, *et al.*** Environmental study of a methicillin-resistant *Staphylococcus aureus* epidemic in a burn unit. *Journal of Clinical Microbiology* 1983; **18**: 683–688.
2. **Farrington M, *et al.*** Outbreaks of infection with methicillin-resistant *Staphylococcus aureus* on neonatal and burns units of a new hospital. *Epidemiology and Infection* 1990; **105**: 215–228.
3. **Kumari DNP, *et al.*** Ventilation grilles as a potential source of methicillin-resistant *Staphylococcus aureus* causing an outbreak in an orthopaedic ward at a district general hospital. *Journal of Hospital Infection* 1998; **39**: 127–133.
4. **Allen KD, Green HT.** Hospital outbreak of multi-resistant *Acinetobacter anitratus*: an airborne mode of spread? *Journal of Hospital Infection* 1987; **9**: 110–119.
5. **Bernards AT, *et al.*** Methicillin-resistant *Staphylococcus aureus* and *Acinetobacter baumanii*: an unexpected difference in epidemiologic behaviour. *American Journal of Infection Control* 1998; **26**: 544–551.
6. **Uduman SA, *et al.*** An outbreak of *Serratia marcescens* infection in a special-care baby unit of a community hospital in United Arab Emirates: the importance of the air conditioner duct as a nosocomial reservoir. *Journal of Hospital Infection* 2002; **52**: 175–180.
7. **Cunney RJ, *et al.*** Investigation of an outbreak of gastroenteritis caused by Norwalk-like virus, using solid phase immune electron microscopy. *Journal of Hospital Infection* 2000; **44**: 113–118.
8. **Brachman PS.** Nosocomial infection – airborne or not? *Proceedings of the International Conference on Nosocomial Infections*. American Hospital Association, 1970: pp. 189–192.
9. **National Audit Office Press Notice.** The management and control of hospital acquired infection in acute NHS trusts in England, 17 February 2000.
10. **Brickner PW, *et al.*** The application of ultraviolet germicidal irradiation to control transmission of airborne disease: bioterrorism countermeasure. *Public Health Reports* 2003; **18**: 99–114.
11. **Fennelly KP, *et al.*** Airborne infection with *Bacillus anthracis* – from mills to mail. *Emerging Infectious Diseases* 2004; **10**: 996–1001.

12. **Nardell EA, *et al.*** Airborne infection: theoretical limits of protection achievable by building ventilation. *American Review of Respiratory Disease* 1991; **144**: 302–306.
13. **Gammaitoni L, Nucci MC.** Using a mathematical model to evaluate the efficacy of TB control measures. *Emerging Infectious Diseases* 1997; **3**: 335–342.
14. **Macher JM, *et al.*** Effect of ultraviolet germicidal lamps in an outpatient waiting room. *Applied Occupational Environmental Hygiene* 1992; **7**: 505–513.
15. **Noakes CJ, Beggs CB, Sleigh PA.** Modelling the performance of upper room ultraviolet germicidal irradiation devices in ventilated rooms: comparison of analytical and CFD methods. *Indoor and Built Environment* 2004; **13**: 477–488.
16. **Menzies D, *et al.*** Effect of ultraviolet germicidal lights installed in office ventilation systems on workers health and wellbeing: double blind multiple crossover trial. *Lancet* 2003; **362**: 1785–1791.
17. **Miller SL, Macher JM.** Evaluation of a methodology for quantifying the effect of room air ultraviolet germicidal irradiation on airborne bacteria. *Aerosol Science and Technology* 2000; **33**: 274–295.
18. **Xu P, *et al.*** Efficacy of ultraviolet germicidal irradiation of upper-room air in inactivating airborne bacterial spores and mycobacteria in full-scale studies. *Atmospheric Environment* 2003; **37**: 405–419.
19. **Wells WF.** *Airborne Contagion and Air Hygiene*. Cambridge, MA: Harvard University Press, 1955.
20. **Riley EC, Murphy G, Riley RL.** Airborne spread of measles in a suburban elementary school. *American Journal of Epidemiology* 1978; **107**: 421–432.
21. **Bailey NT.** *The Mathematical Theory of Epidemics*. London: Griffin & Co., 1957.
22. **Kermack WO, McKendrick AG.** A contribution to the mathematical theory of epidemics. *Proceedings of the Royal Society of London Series A* 1927; **115**: 700–721.
23. **Daley DJ, Gani J.** Epidemic modelling, an introduction. In: Cannings C, Hoppensteadt FC, Segel LA, eds. *Cambridge Studies in Mathematical Biology 15*, Cambridge, UK: Cambridge University Press, 1999.
24. **Castillo-Chavez C, Feng Z.** To treat or not to treat: the case of tuberculosis. *Journal of Mathematical Biology* 1997; **35**: 629–656.
25. **Massad E, *et al.*** Modelling the interaction between AIDS and tuberculosis. *Mathematical and Computational Modelling* 1993; **17**: 7–21.
26. **Hawker J, *et al.*** *Communicable Disease Control Handbook*. Oxford, UK: Blackwell Science, 2001: pp. 124–126.
27. **Chadwick PR, *et al.*** Management of hospital outbreaks of gastro-enteritis due to small round structured viruses. *Journal of Hospital Infection* 2000; **45**: 1–10.
28. **Farr BM.** Nosocomial gastrointestinal tract infections. In: Mayhall CG, ed. *Hospital Epidemiology and Infection Control*, 3rd edn. London, UK: Lippincott-Williams & Wilkins, 2004: pp. 351–383.
29. **Gammaitoni L, Nucci MC.** Using Maple to analyze a model for airborne contagion. *MapleTech* 1994; **4**: 2–5.
30. **Beggs CB, *et al.*** The transmission of tuberculosis in confined spaces: an analytical study of alternative epidemiological models. *International Journal of Tuberculosis and Lung Disease* 2003; **7**: 1015–1026.
31. **Rudnick SN, Milton DK.** Risk of airborne infection transmission estimated from carbon dioxide concentration. *Indoor Air* 2003; **13**: 237–245.
32. **Beggs CB, *et al.*** The use of engineering controls to disinfect *Mycobacterium tuberculosis* and airborne pathogens in hospital buildings. *Indoor and Built Environment* 2000; **9**: 17–27.
33. **Riley RL, Knight M, Middlebrook G.** Ultraviolet susceptibility of BCG and virulent tubercule bacilli. *American Review of Respiratory Disease* 1976; **113**: 413–418.
34. **Hutton MD, *et al.*** Nosocomial transmission of tuberculosis associated with a draining abscess. *Journal of Infectious Diseases* 1990; **161**: 286–295.
35. **Noakes CJ, Beggs CB, Sleigh PA.** Effect of room mixing and ventilation strategy on the performance of upper room ultraviolet germicidal irradiation systems. *Proceedings of ASHRAE IAQ 2004*, Tampa, Florida, 15–17 March.
36. **Cooper BS, Medley GF, Scott GM.** Preliminary analysis of the transmission dynamics of nosocomial infections: stochastic and management effects. *Journal of Hospital Infection* 1999; **43**: 131–147.
37. **Catanzaro A.** Nosocomial tuberculosis. *American Review of Respiratory Disease* 1982; **125**: 559–562.
38. **Wells WF, Wells MW, Wilder TS.** The environmental control of epidemic contagion 1. An epidemiologic study of radiant disinfection of air in day schools. *American Journal of Hygiene* 1942; **35**: 97.

The ventilation of multiple-bed hospital wards: Review and analysis

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Background: Although the merits of ventilating operating theatres and isolation rooms are well known, the clinical benefits derived from ventilating hospital wards and patient rooms are unclear. This is because relatively little research work has been done in the ventilation of these areas compared with that done in operating theatres and isolation rooms. Consequently, there is a paucity of good quality data from which to make important decisions regarding hospital infrastructure. This review evaluates the role of general ward ventilation to assess whether or not it affects the transmission of infection.
Methods: A critical review was undertaken of guidelines in the United Kingdom and United States governing the design of ventilation systems for hospital wards and other multibed rooms. In addition, an analytical computational fluid dynamics (CFD) study was performed to evaluate the effectiveness of various ventilation strategies in removing airborne pathogens from ward spaces.
Results: The CFD simulation showed the bioaerosol concentration in the study room to be substantially lower (2467 cfu/m^3) when air was supplied and extracted through the ceiling compared with other simulated ventilations strategies, which achieved bioaerosol concentrations of 12487 and 10601 cfu/m^3, respectively.
Conclusions: There is a growing body of evidence that the aerial dispersion of some nosocomial pathogens can seed widespread environmental contamination, and that this may be contributing to the spread infection in hospital wards. *Acinetobacter* spp in particular appear to conform to this model, with numerous outbreaks attributed to aerial dissemination. This suggests that the clinical role of general ward ventilation may have been underestimated and that through improved ward ventilation, it may be possible to reduce environmental contamination and thus reduce nosocomial infection rates. (Am J Infect Control 2008;36:250-9.)

Although the merits of ventilating operating theatres[1-5] and isolation rooms[3,6] are well known, the clinical benefits derived from ventilating hospital wards and patient rooms are unclear. This is because relatively little research work has been done on the ventilation of these areas compared with operating theatres and isolation rooms. Consequently, there is a paucity of good-quality data from which to make important decisions regarding hospital infrastructure. Indeed, with respect to general ward ventilation, much of what has been written has tended to focus on the interpretation of building codes and regulations rather than addressing fundamental issues regarding the clinical role of ward ventilation. In light of this situation, we conducted this review to evaluate the role of general ward ventilation and to assess whether or not it affects the transmission of infection in health care facilities. We evaluate the advantages and disadvantages of the various approaches taken and compare these with current thinking regarding the spread of infection in hospital wards.

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WARD VENTILATION

Although a plethora of guidelines on the ventilation of health care facilities have been published,[7-10] the vast majority of these are concerned with specialist facilities, such as operating theatres, isolation rooms, and bronchoscopy suites, where the risks associated with the airborne transmission of infection are well characterized. In comparison, guidelines regarding the ventilation of general ward spaces, patient rooms, and intensive care wards are much sparser and often vague in nature. For example, in the United Kingdom, National Health Technical Memorandum HTM 2025 (Design Considerations, Ventilation in Health Care Premises) makes little reference to the ventilation of clinical spaces other than operating theatres.[7] Indeed, other than encouraging the use of full fresh air systems, HTM 2025 specifies no criteria for the ventilation of ward spaces. In an era where hospital-acquired infection (HAI) is a major worldwide problem, this may seem to be a surprising omission. Ward ventilation could play an important role in controlling the spread of HAI, although there is a generally held view that most nosocomial infections are transmitted by the contact route (ie, through the hands of health care workers).[11] Indeed, only a few nosocomial diseases of a bacterial or fungal etiology, such as tuberculosis

(TB), legionnaire's disease, and pulmonary aspergillosis, are readily accepted as being transmitted by an airborne route. Consequently, ward ventilation systems are generally specified in terms of providing patient comfort and minimizing energy costs, rather than for clinical reasons. In short, ward ventilation is perceived as having little impact on the transmission of HAI and thus is not rigorously specified. Notwithstanding this, there is growing evidence[12-14] indicating that airborne pathogens may play a greater role in the spread of infection within wards than hitherto expected. If this is the case, then the potential of ward ventilation systems to control infection may have been greatly underestimated, and there is a need to reevaluate the basis on which such systems are specified.

SINGLE- AND MULTIPLE-BED ROOMS

It is impossible to address the issue of ward ventilation without first considering the nature of patient rooms. In many parts of the world, including the United Kingdom, it is common practice to have multiple-bed wards, often subdivided into bays containing 4 or 6 patients. However, in the United States, the practice is to place patients in single rooms where possible, with a maximum number of 2 patients per room.[9] Indeed, the 2006 American Institute of Architects (AIA) guidelines now mandate single rooms for all patients in new hospitals.[15] Consequently, whereas European hospitals frequently contain multiple-bed wards, their counterparts in the United States are composed largely of single- and 2-patient rooms. However, the AIA's requirement for single-bed patient rooms in US hospitals does not extend to critical care facilities, where multiple-bed wards are permitted (and indeed are the norm).

EVIDENCE FOR AERIAL DISSEMINATION

Before focusing on ventilation systems, it is worth considering the evidence regarding the airborne transmission of infection in hospitals. A full discussion of this topic is beyond the scope of this review, however, and thus we give only a brief overview of the evidence for the aerial dissemination of pathogens within the ward environment. This overview is restricted to those infections that normally are not considered airborne in nature and thus does not cover TB, legionnaire's disease, or pulmonary aspergillosis, which are already accepted as being transmitted by the airborne route.

There is a large body of evidence supporting the view that staphylococci are frequently disseminated by the aerial route in the clinical environment. Contaminated clothing and bedding of colonized patients release *Staphylococcus aureus* into the air when disturbed.[13,16,17] During bed-making in particular, staphylococci-bearing particles are liberated into the air and deposited on surfaces within the environment.[12,13,18] This process was well illustrated by Rutala et al,[19] who investigated a methicillin-resistant *S aureus* (MRSA) outbreak in a burn unit and found that MRSA accounted for 16% of all bacterial isolates sampled from the air and 31% of the isolates cultured from elevated surfaces. Because health care personnel or patients are unlikely to touch elevated surfaces, the presence of MRSA isolates on these surfaces suggests that staphylococci are frequently transported through the air. Although the clinical relevance of staphylococcal contamination is not fully known, a correlation between environmental contamination and patient infection/colonization has been noted by several researchers. Wilson et al[20] observed a strong correlation between the presence of MRSA-colonized or -infected patients and air samples yielding MRSA in an ICU. Boyce et al[21] found a similar correlation, with environmental contamination occurring in the rooms of 73% of MRSA-infected patients. In another study, Shiomori et al,[13] sampling the environment around MRSA-colonized or -infected patients under normal conditions, found an average of 4.7 cfu/m^3 MRSA-carrying particles in the air near infected patients; however during bed making, this figure increased to 116 cfu/m^3, confirming that this activity results in considerable aerosolization of staphylococci. Collectively, these findings suggest that MRSA-colonized or -infected patients readily contaminate their surroundings by aerial dissemination. Although the clinical relevance of this finding is incompletely understood, it may be that the resulting environmental contamination both increases the spread of the MRSA infection and prolongs any outbreaks that occur.

S aureus often colonizes the anterior nares, with about 20% of healthy people having persistent nasal colonization and about 60% displaying intermittent carriage.[22] It appears that the nose acts as a reservoir, which then supports colonization of the skin surface of most carriers; eradication of staphylococci from the nose is generally accompanied by eliminating *S aureus* from the other colonized body sites.[23] Given that humans liberate approximately 3×10^8 squama per day[24] and that each skin squame may carry > 100 bacteria,[25] there is a strong likelihood that the nares of susceptible adults can become colonized with *S aureus* simply by inhaling particles from the air,[26] and that this is likely to be a dose-related response.[27] Indeed, this has led one commentator to conclude that ''the principal mode of transmission is via transiently contaminated hands of hospital personnel…airborne transmission seems important in the acquisition of nasal carriage.''[28]

Hospital ventilation systems also have been implicated in MRSA outbreaks. Kumari et al[29] presented

evidence of patients acquiring MRSA as a result of periodic dispersion of MRSA-contaminated dusts from air grills. Cleaning the grills and ensuring continuous operation of the ventilation system prevented further outbreaks of MRSA infection. Wagenvoort et al[30] found MRSA isolates on ventilation grills in an orthopedic ward, and Cotterill et al[31] identified colonies of MRSA in the exhaust air from an isolation room as the source of an outbreak in an intensive care unit; the MRSA bacteria were reentering the unit through an open window.

Another important nosocomial pathogen for which there is growing evidence of aerial dissemination is *Acinetobacter*. *Acinetobacter* spp are the only gram-negative bacteria that form part of the normal skin microflora, with colonization in 25% to 43% of healthy people.[32] Unlike most gram-negative bacteria, they are particularly hardy and survive well in the environment.[32-34] Consequently, *Acinetobacter* spp can be readily disseminated on skin squama in a manner similar to *S aureus*.

Numerous studies have implicated the aerial dissemination of *Acinetobacter* spp bacteria in the transmission of infection. Allen and Green[35] were the first to suggest airborne dissemination of *Acinetobacter*-carrying particles. Investigating an outbreak of multiply antibiotic-resistant *Acinetobacter anitratus* in an intensive care unit (ICU), a medical ward, and 3 neurosurgical wards, these investigators cultured the outbreak organism from 16 of 82 settle plates, leading them to conclude that widespread aerial dissemination of *Acinetobacter* spp was occurring. Based on results of Allen and Green and of their own study, Das et al[36] suggested that movement of heavily contaminated bed curtains could promote the airborne spread of *Acinetobacter* spp Further evidence of the aerial dissemination of *Acinetobacter* spp came from a study in Hong Kong, in which Houang et al[37] placed 70 settle plates in an ICU and 120 (in total) in 4 surgical wards. Remarkably, 96% of plates in the ICU and 89% in the surgical wards were culture-positive, demonstrating widespread airborne dispersal. In a Danish study, Gerner-Smidt[38] recovered an outbreak of strain *Acinetobacter calcoaceticus* subspecies *anitratus* from the air in an ICU using both settle plates and a slit sampler. Others also have shown that *Acinetobacter* spp can be readily cultured from hospital air.[39-42]

Some of the strongest evidence regarding the airborne spread of *Acinetobacter* spp comes from outbreaks of *Acinetobacter baumannii* in 3 Dutch hospitals (2 of which experienced outbreaks despite isolation precautions). Bernards et al[14] found strong evidence of *Acinetobacter* transmission by the airborne route. In the hospitals that experienced outbreaks, the source patients were isolated in nonpressurized rooms, whereas in the other hospital, the infectious patient was isolated in a negatively pressurized room. In the hospitals with outbreaks, the settle plates, located inside and outside the isolation rooms, grew the outbreak strain, whereas in the third hospital, plates placed in the same location proved to be culture-negative. Thus, Bernards et al surmised that airborne transmission was occurring.

Clostridium difficile–associated disease (CDAD), a major problem on elderly care wards, is known to be associated with environmental contamination.[43-45] It has been postulated that environmental contamination might result from aerial dissemination of *C difficile* spores, which can survive on inanimate surfaces for several months.[46,47] Evidence supporting this supposition comes from a 22-month surveillance study in which air vents and high horizontal surfaces were found to be contaminated with *C difficile*, suggesting the aerial dissemination of isolates.[45,48] Moreover, numerous studies have found *C difficile* isolates on patients' bedding.[47,49,50] Given that bed-making is known to liberate large numbers of bacterial-carrying particles into the air,[51-53] the presence of *C difficile* on patient's bed linen suggests that *C difficile* spores or vegetative cells may be disseminated into the air by this route. Indeed, in a recent study on an elderly care ward,[54] we managed to culture *C difficile* from the air on 23 separate occasions over a 2-day period, with counts ranging from 53 to 426 cfu/m^3 of air, suggesting the presence of a significant source within the ward during the sampling period.

Although the foregoing discussion is far from exhaustive, it illustrates the fact that in hospital wards, pathogenic microorganisms are frequently liberated into the air in relatively large quantities. If not ventilated from the ward space, these airborne pathogens will cause widespread environmental contamination as they settle on surfaces within the ward, thus seeding potential reservoirs of infection. Given this situation, there is reason to believe that if used appropriately, ward ventilation may help control the spread of some nosocomial infections.

VENTILATION GUIDELINES IN THE UNITED KINGDOM AND UNITED STATES

Table 1 summarizes the ventilation and comfort standards for general ward spaces and ICUs as promulgated by the various regulatory bodies in the United States and United Kingdom. In the United States, the AIA guidelines regulate the design of health care facilities.[9] The AIA guidelines are supplemented by the guidelines of the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE).[10] In the United Kingdom, HTM 2025, published by the Department of Health, is used to guide designers of health care facilities.[7]

Table 1. Comparison of the various guidelines governing the ventilation of general and intensive care ward spaces in the United Kingdom and the United States

Code	Country	Pressure Relationship	Minimum Outdoor Air Change Rate (AC/h)	Minimum Total Air Change Rate (AC/h)	Design Air Temperature (°C)	Design Relative Humidity (%)
Patient rooms/general wards						
AIA	United States	Neutral	2	6	21 to 24	Not specified
ASHRAE	United States	Neutral	2	6	21 to 24	30 to 60
HTM 2025	United Kingdom	Neutral	Not specified*	Not specified†	20 to 22	40 to 60
Intensive care wards						
AIA	United States	Neutral	2	6	21 to 24	30 to 60
ASHRAE	United States	Neutral	2	6	21 to 24	30 to 60
HTM 2025	United Kingdom	Neutral	Not specified*	Not specified†	20 to 22	40 to 60

*Minimum outdoor air (ie, fresh air) rate of 8 l/s per person specified.
†100% outdoor air encouraged.

From Table 1, it can be seen that the guidelines in the United States are more prescriptive than those in the United Kingdom, the main difference being that the AIA guidelines specify minimum ventilation rates (ie, air change rates), whereas HTM 2025 does not (other than requiring a minimum fresh air rate of 8 l/s per person). In addition, the AIA guidelines permit recirculation of ward air, whereas HTM 2025 strongly discourages (although does not completely outlaw) the use of recirculation systems. With regard to the comfort conditions, Table 1 shows that the internal design requirements are similar in the United Kingdom and United States.

In the United States, the air supplied to patients in general wards must be first prefiltered (minimum efficiency reporting value [MERV] 7, 30% dust spot efficiency), and then filtered to a MERV 14 or 15 standard (90% to 95% dust spot efficiency) before delivery to the ward space.[10] This standard of filtration ensures 85% to 95% arrestance efficiency for 0.3 to 1.0 μm particles and > 90% efficiency for > 1.0 μm particles. Given that skin squama are generally 4 to 25 μm in size, this level of filtration should ensure that the air supplied to the ward space is relatively clean, despite the fact that a large proportion of this air may be recirculated. In the United Kingdom, where ward mechanical ventilation systems tend to be full fresh air, HTM 2025 is somewhat vague on the subject of filtration. It simply specifies EU5 filters (50% dust spot efficiency) for ''general applications where décor protection is not critical'' and EU6 filters (70% dust spot efficiency) for general applications where décor protection is particularly important, making no reference to clinical requirements.

DRIVERS

Analysis of HTM 2025 reveals that with respect to the ventilation of general ward spaces, the guidance notes are driven by comfort and economic issues rather than by clinical considerations. As long as reasonable patient comfort conditions are maintained, the regulations are not concerned about whether ventilation is achieved by natural or mechanical means. Indeed, HTM 2025 actively encourages natural ventilation, although it is very vague as to how this should be achieved in practice. This reliance on natural ventilation may explain in part why HTM 2025 does not specify minimum ventilation rates. With regard to mechanical ventilation, HTM 2025 simply states that ''where mechanical supply systems are required, the fresh air should be tempered and filtered before being delivered to the space, to avoid discomfort,'' and with regard to air-conditioning, that ''air-conditioning is only required in a very small number of areas within health care buildings; and due to the capital and running cost implications, its inclusion should be kept to a minimum.''

Although HTM 2025 actively promotes the use of natural ventilation, it does acknowledge that in larger health care facilities, where internal spaces are greater (ie, deeper) than 6 m from a facade, mechanical ventilation generally will be required. In such situations, it recommends using a 100% fresh air system, presumably to avoid the recirculation of airborne pathogens. Such a system allows the use of a lower standard of filtration compared with similar ventilation systems in the United States.

The regulations in the United States take a different approach to those in the United Kingdom, specifying minimum fresh air and total ventilation rates for different applications. This is due primarily to the fact that the United States experiences climatic extremes that preclude the use of natural ventilation for much of the year. Consequently, mechanical ventilation and air-conditioning systems are used much more widely in the United States than in the United Kingdom. The provision for air recirculation in the AIA guidelines primarily reflects the desire to reduce energy costs while

still maintaining a comfortable internal room condition. This in turn explains why the filtration standards are much higher in the United States than in the United Kingdom. Clearly, the drafters of the AIA guidelines recognized the infection risks associated with recirculating unfiltered air. Notwithstanding this, to allow for greater flexibility, mechanical ventilation systems that use 100% fresh air are frequently installed in US hospitals, thus permitting the use of patient rooms as airborne infection isolation rooms.

Along with comfort and economic issues, infection control appears to be a driving force behind policy decisions in the United States. In the 2001 AIA guidelines, the total air change rate requirement for patient rooms was increased from 2 air changes per hour (AC/h) to 6 AC/h to improve patient comfort.[6] The increased total ventilation rate also provided a measure of protection against patients with undiagnosed TB.[55] Unlike HTM 2025, which puts little emphasis on room humidity, the ASHRAE guidelines address the effects of high humidity on the proliferation of pathogens within the clinical environment, specifying the maintenance of ward relative humidity at 30% to 60%.[10] Achieving this level necessitates the use of air-conditioning in many parts of the United States during the summer months, increasing energy costs. It is noteworthy that neither the US or the UK guidelines attempt to specify airflow patterns within ward spaces, but instead rely on good air mixing to promote a good dilution affect.

PATIENT DENSITY AND ACTIVITY

One potential weakness of simply quoting required air change rates is that this approach takes no account of patient density—the ventilation rate is determined solely by the room volume, rather than the number of occupants. In reality, as ward occupancy levels increase, bioaerosol production within the space also increases. Any increase in the number of beds in a ward space will be accompanied by a corresponding increase in the number of nursing staff and visitors, all of whom will liberate microorganisms into the air. Indeed, even a modest increase in the number of patients may result in a substantial increase in bioaerosol production. Thus, if a ventilation system is required to control the bioaerosol level in a ward space, then it may be desirable to link its specification to ward occupancy levels in some way. In the United States, the AIA guidelines do this by specifying the size of rooms and strictly limiting the number of patients per room.[15]

In reality, bioaerosol production on wards is not constant, but varies greatly throughout the day with changes in activity level. In a recent study conducted in a respiratory ward, we found that such activities as bed-making, patient washing, and ward rounds produced significant increases in the number of airborne particles > 3 μm in size liberated into the air.[53] This finding is intuitive, given that large numbers of skin squama are likely to be liberated into the air during these activities.

INFLUENCES ON PATHOGEN TRANSPORT AND REMOVAL

Both the UK and US guidelines assume the use of dilution ventilation when ventilating general ward spaces. Such a strategy relies on good air mixing within the room space and generally is achieved by supplying clean filtered air in through diffusers in the ceiling and extracting contaminated air out through grills also located in the ceiling. With this type of ventilation system and full air mixing, the steady-state contaminant level, C_e, achieved in the ward space can be calculated as

$$C_e = \frac{q_c}{Q_v}, \tag{1}$$

where q_c is the generation rate of biological contaminants in the room space (cfu/s) and Q_v is the volume flow rate of the ventilation air (m^3/s). This equation shows that the greater the ventilation air flow rate, the lower the contaminant concentration level in the room air, and the greater the air change rate, the shorter the average residence time of bioaerosol particles in the room space. At a ventilation rate of 2 AC/h, the average particle residence time is 30 minutes; increasing the rate to 6 AC/h decreases the average residence time to 10 minutes.

PARTICLE SIZE DISTRIBUTION

The ability of any given ventilation system to remove particles from a room space does not depend solely on the air change rate. In reality, air in ventilated rooms usually is far from fully mixed,[56] and the concentration of bioaerosols depends on the location of the bioaerosol source, the local airflow patterns, and the size distribution of the particles. Very small particles fall through the air very slowly and thus are much more likely to be removed by the ventilation system, whereas large particles are much more likely to remain in the room space, albeit displaced somewhat by the room air currents before settling out. The terminal velocity of particles falling through air can be calculated using Stokes' law,

$$V_t = \frac{\rho_p d^2 g}{18\eta} C_c, \tag{2}$$

where ρ_p is the density of the particle (kg/m^3), d is the particle diameter (m), g is the acceleration due to gravity

Table 2. Terminal velocity of falling particles, assuming a particle density of 1000 kg/m^3

Particle Diameter (μm)	Terminal Velocity (mm/s)	Time Required to Fall 2 m (minutes)
1	0.036	932.1
2	0.133	251.1
4	0.504	66.2
8	2.001	16.7
16	7.791	4.2
32	31.886	1.0

(9.81 m/s^2), η is the viscosity of air (1.78×10^{-5} kg/ms), and C_c is the Cunningham slip-correction factor.

To highlight the significance of eq (2), Table 2 presents information demonstrating how the terminal velocity and duration of fall of a typical particle varies with its diameter. The table shows that small changes in diameter greatly influence settling velocity, with particles < 4 μm taking hours to fall 2 m in a still room, compared with particles > 4 μm, which take minutes to fall the same distance. Although air flow patterns in room spaces can be highly complex, it is possible to make some general statements about the fate of different-sized bioaerosol particles liberated into the air. Because of their small mass and very slow terminal velocity, most particles < 5 μm are likely to be extracted from the room space, although some eventually may be deposited on surfaces after having first been transported some distance. In comparison, the fate of larger particles is somewhat less clear. Some will be removed completely from the room space by the ventilation system, whereas many others (usually the largest) will be deposited on various surfaces throughout the room space. Therefore, particle size has a considerable affect on the eventual fate of microorganisms liberated into the air.[57] Microorganisms aerosolized in respiratory droplet nuclei are most likely to be extracted from the ward space by the ventilation air, whereas those released on larger skin squama are much more likely to result in environmental contamination of room surfaces.

VENTILATION STRATEGY

Notably, the guidelines for ventilating general ward spaces in both the United Kingdom and the United States make no attempt to specify airflow patterns and assume that dilution ventilation will be used. This situation may be due in part to the complexity of airflow patterns in rooms, as alluded to earlier; however, it is perhaps worth considering the affect of air flow direction on bioaerosol concentration generated within a ward space. Consequently, we carried out a short CFD study to explore this affect by simulating 3 different ventilation strategies in an empty 32-m^3 room, as shown in Figure 1. The study was done using Fluent 6.2 CFD software (ANSYS, Canonsburg, PA) with an unstructured tetrahedral grid containing approximately 540,000 cells. A standard k-ε turbulence model with enhanced wall treatment was used, and a no-slip condition was applied at the walls. The model was treated as isothermal in all cases. The 3 ventilation regimes were as defined in Table 3. In cases 1 and 2, the supply air diffuser was modeled by a series of parabolic velocity profiles representing the grill louvers, with the air entering at a downward angle of 45 degrees in case 1 and entering horizontally in case 2. In case 3, the supply air entered at a downward angle of 45 degrees from the sides of the ceiling located box, to represent a 4-way diffuser. In all cases, the total air flow rate was set to be equivalent to 6 AC/h, and a zero pressure condition was defined on the extract diffuser boundary.

Bioaerosols were modeled using a transported scalar to represent the concentration of airborne particles. This assumes that all of the bioaerosol particles remain suspended in the air, with none settling out. Although this assumption may not be true for larger skin squama, it is a good approximation for smaller particles

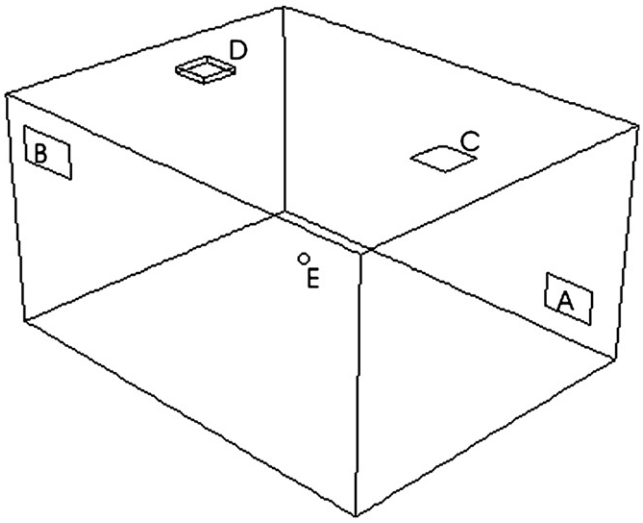

Fig 1. Geometry of the room showing the location of ventilation grilles (A to D) and the bioaerosol source (E).

Table 3. Ventilation regimes simulated using the CFD model

Ventilation Regime	Supply Diffuser Location	Extract Diffuser Location
1 (low–high)	A	B
2 (high–low)	B	A
3 (ceiling)	D	C

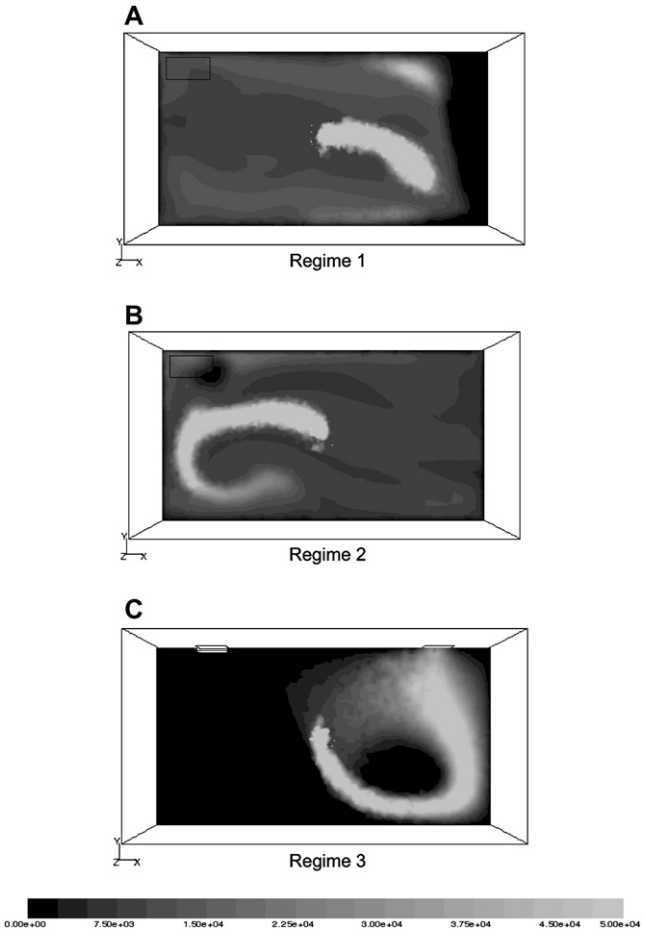

Fig 2. Bioaerosol concentration contour plots on an *x*–*y* vertical plane located centrally in the room and facing diffuser A. *A*, Regime 1. *B*, Regime 2, *C*, Regime 3. Concentration in cfu/m^3.

(ie, < 10 μm). The bioaerosols are assumed to enter the space at a constant rate over a small volume (0.1 m^3) located in the center of the room (point E in Fig 1), representing a point source due to an infectious patient. This is modeled through a constant volumetric source term and a momentum term of 0.1 N/m to represent the inertia of the particles on their release.

We solved the model just described using second-order discretization and a segregated implicit solver to find steady-state simulations for the 3 ventilation cases. Convergence was good in all 3 models, with a mass imbalance of $< 0.1\%$ in the final solutions. Results from the CFD simulations are presented in Figure 2 and Table 4. Figure 2 shows bioaerosol concentration contours plotted on a vertical plane through the center of the room looking toward diffuser A. For clarity, the maximum contour plotted is 50,000, although the highest concentration close to the source is of the order of 1,700,000. Table 4 presents the volume average bioaerosol concentration throughout the entire room, calculated for each regime using the postprocessing tools in Fluent.

Table 4. Volume-averaged bioaerosol concentration calculated from CFD simulation results for 3 ventilation regimes

Ventilation Regime	Volume Average Concentration (cfu/m^3)
1 (low–high)	12,487
2 (high–low)	10,601
3 (ceiling)	2467

Both the average data and the contour plots show significant variation between the 3 ventilation regimes. The lowest average value is seen in case 3, in which the supply and extract are located in the ceiling. Cases 1 and 2 have concentrations of similar orders of magnitude, up to 5 times greater than that of case 3. The reason for this difference is apparent from the contour plots. In cases 1 and 2, the airflow distributes the contaminant across the plane, and in fact draws the plume emitted from the source initially toward the supply diffuser side of the room. This means that the airflow promotes mixing in the room, following the classic theory of the dilution effect. But the contour plots for case 3 reveal an airflow pattern such that the contaminant is very effectively removed from the room before mixing occurs. Thus, there is a high bioaerosol concentration between the source location and the extract grill, but little contamination distributed across the rest of the plotted plane.

Care should be taken to distinguish between piston ventilation (as shown by regime 1 in the foregoing CFD model) and displacement ventilation systems. The latter relies on the buoyancy effects caused when cool air supplied at low level and is warmed when coming into contact with room occupants. Displacement ventilation systems have been used successfully in many applications, but their suitability in clinical applications is unclear. This is because in the ward environment, microorganisms often are projected into the air with some force, either through respiratory expulsions (eg, coughing)[58] or as a result of activities (eg, bedmaking).[51-53] Consequently, bioaerosols rapidly become decoupled from the buoyancy-driven plumes that surround room occupants when displacement ventilation is used. In a recent experimental study, Qian et al[59] found that with displacement ventilation, when patients cough, the exhaled jets thus formed penetrated long distances, resulting in ''trapped'' regions of high concentrations of exhaled droplet nuclei that could not be not rapidly dissipated by the ventilation air, but with dilution (ie, mixing) ventilation, the exhaled

jets penetrated only a short distance and were quickly diluted by the ventilation air. The investigators thus concluded that the type of ventilation strongly influenced bed spacing, with displacement ventilation necessitating spacing the beds further apart compared with when dilution ventilation is used. In addition, Zhao et al,[57] in a theoretical CFD study of an empty room, found that whereas displacement ventilation generally reduced particle deposition on surfaces, it greatly increased the number of particles suspended in the room air, particularly larger particles (ie, $>$ 10 μm). They concluded from this somewhat surprising finding that whereas the unidirectional air flow enabled smaller particles to escape the space, the larger particles attempted to settle in the opposite direction and thus remained suspended in the air for long periods.

These published results, together with the CFD model presented in this study, serve to further highlight the complexity of air flow in rooms and its dependence on the local room design. The findings from studies on displacement ventilation suggest that this ventilation method may not be well suited to general ward spaces, and that dilution ventilation can better control the spread of infection. Although in the model presented herein, 3 different dilution ventilation regimes are considered, drawing general conclusions about the most appropriate design for a hospital environment is difficult. Nonetheless, the results of the present study and those from simulations of a TB ward presented in a previous study demonstrate that the ventilation system within a single room space can have a significant affect on the distribution of airborne infectious material, and thus on the risk of cross-infection.[60] This suggests that although it may not be appropriate for inclusion in guidelines, ventilation system designers should seriously consider using CFD and other simulation tools to optimize ventilation design to minimize infection risk, and that further studies are needed to properly understand the influence of the airflow patterns.

DISCUSSION

From the foregoing discussion, it is clear that ventilation systems for general wards and patient rooms are specified using criteria that differ little from those used for nonclinical spaces. The guidelines in both the United Kingdom and the United States avoid any discussion of the risks posed by airborne microorganisms, but focus on providing a comfortable environment. This is understandable, given that patient comfort is of great importance and that the clinical risk posed by many airborne pathogens is unclear. Nonetheless, there is growing evidence that the aerial dispersion of some nosocomial pathogens is seeding widespread environmental contamination that may be promoting infection in immunocompromised patients.[11,12,21] *Acinetobacter* spp in particular appears conform to this model, with numerous outbreaks attributed in to its aerial dissemination.[61] If the aerial dissemination of microbes is indeed contributing to overall levels of infection in any way, then ward ventilation becomes very important, because ventilation design has a considerable affect on the eventual fate of airborne microorganisms. It may be possible to greatly reduce environmental contamination and thus minimize HAI through improved ventilation.

Given the considerable body of evidence indicating that aerial dissemination of skin squama from such activities as bed-making has the potential to cause widespread environmental contamination, air flow patterns within ward spaces would seem to be an issue of some importance. This is particularly true if it is important to ensure that clinically sensitive surfaces remain free of microbial contamination. Toward this end, piston-type ventilation may offer some benefits over conventional dilution systems. In contrast, displacement ventilation that relies on natural buoyancy plumes appears to offer only modest benefits, because the air velocities associated with this type of ventilation generally are very low. Indeed, there is some evidence that displacement ventilation is rather poor at removing larger ($>$ 10 μm) particles from the air; [57] however, because of the limited number of studies undertaken, these observations cannot be considered definitive for all situations.

CFD modeling is a powerful tool for investigating ventilation strategies. The models used in this work have yielded useful data on the spread of an idealized source of contamination in an isothermal situation. This technique possibly may be further extended to include more detailed models of the physics of contamination transport—for example, the temperature and relative humidity of the air, to account for buoyancy of particles and for changes in particle size due to evaporation. But although more sophisticated models may be developed, producing accurate simulations is impossible without the input of good data describing the particle source and the size range and volume of the particles produced. In particular, it is important to allow for heat sources within the room space, because these have been shown to significantly influence both air flow and thermal comfort.[62-64]

Although there is strong evidence that good ward ventilation provides health benefits, because of the complexity of the mechanisms involved, the level of ward ventilation required to prevent HAI is not known. Indeed, in a recent study, Li et al[65] concluded that the ''strong and sufficient evidence of the association between ventilation, the control of airflow direction in buildings, and the transmission and spread of

infectious diseases supports the use of negatively pressurized isolation rooms for patients with these diseases in hospitals, in addition to the use of other engineering control methods. However, the lack of sufficient data on the specification and quantification of the minimum ventilation requirements in hospitals, schools and offices in relation to the spread of airborne infectious diseases, suggest the existence of a knowledge gap. Our study reveals a strong need for a multidisciplinary study in investigating disease outbreaks, and the impact of indoor air environments on the spread of airborne infectious diseases.'' This statement is very apt, because it reflects both our opinion and the frustrations of other researchers in the field. There is a clear knowledge gap regarding the extent to which airborne pathogens, respirable or otherwise, contribute to infection. Furthermore, there is a lack of good-quality data from which to make decisions regarding the minimum ventilation rates required to prevent infection. Good data will help those drafting future guidelines for ventilation designers reach firm conclusions.

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References

1. Blowers R, Mason GA, Wallace KR, Walton M. Control of wound infection in a thoracic surgery unit. Lancet 1955;269:786-94.
2. Shooter RA, Taylor GW, Ellis G, Ross JP. Post-operative wound infection. Surg Gynecol Obstetr 1956;103:257-62.
3. Leung M, Chan AH. Control and management of hospital indoor air quality. Med Sci Monit 2006;12:SR17-23.
4. Smyth ET, Humphreys H, Stacey A, Taylor EW, Hoffman P, Bannister G. Survey of operating theatre ventilation facilities for minimally invasive surgery in Great Britain and Northern Ireland: current practice and considerations for the future. J Hosp Infect 2005;61:112-22.
5. Chow TT, Yang XY. Ventilation performance in operating theatres against airborne infection: review of research activities and practical guidance. J Hosp Infect 2004;56:85-92.
6. Ninomura P, Bartley J. New ventilation guidelines for health-care facilities. ASHRAE J 2001;43:29-33.
7. National Health Service. Design considerations: ventilation in healthcare premises. Health technical memorandum 2025. London: National Health Service Estates; 1994.
8. Sehulster LM, Chinn RYW, Arduino MJ, Carpender J, Donlan R, Ashford D, et al. Guidelines for environmental infection control in healthcare facilities: recommendations from CDC and Healthcare Infection Control Practices Advisory Committe (HICPAC). Atlanta (GA): US Department of Health and Human Services, Centers for Disease Control and Prevention; 2003.
9. American Institute of Architects. Guidelines for design and construction of hospital and health care facilities. Washington, DC: American Institution of Architects; 2001.
10. American Society of Heating, Refrigeration and Air-Conditioning Engineers. HVAC design manual for hospitals and clinics. Atlanta (GA): American Society of Heating, Refrigeration and Air-Conditioning Engineers; 2003.
11. Beggs CB, Noakes CJ, Shepherd SJ, Kerr KG, Sleigh PA, Banfield K. The influence of nurse cohorting on hand hygiene effectiveness. Am J Infect Control 2006;34:621-6.
12. Shiomori T, Miyamoto H, Makishima K. Significance of airborne transmission of methicillin-resistant *Staphylococcus aureus* in an otolaryngology–head and neck surgery unit. Arch Otolaryngol Head Neck Surg 2001;127:644-8.
13. Shiomori T, Miyamoto H, Makishima K, Yoshida M, Fujiyoshi T, Udaka T, Inaba T, Hiraki N. Evaluation of bedmaking-related airborne and surface methicillin-resistant *Staphylococcus aureus* contamination. J Hosp Infect 2002;50:30-5.
14. Bernards AT, Frenay HM, Lim BT, Hendriks WD, Dijkshoorn L, van Boven CP. Methicillin-resistant *Staphylococcus aureus* and *Acinetobacter baumannii*: an unexpected difference in epidemiologic behavior. Am J Infect Control 1998;26:544-51.
15. American Institution of Architects. Guidelines for design and construction of health care facilities. Washington, DC: American Institution of Architects; 2006.
16. Noble WC, Davies RR. Studies on the dispersal of staphylococci. J Clin Pathol 1965;18:16-9.
17. Solberg CO. A study of carriers of *Staphylococcus aureus*. Acta Med Scand 1965;178(suppl):436.
18. Noble WC. The dispersal of staphylococci in hospital wards. J Clin Pathol 1962;15:552-8.
19. Rutala WA, Katz EB, Sherertz RJ, Sarubbi FA Jr. Environmental study of a methicillin-resistant *Staphylococcus aureus* epidemic in a burn unit. J Clin Microbiol 1983;18:683-8.
20. Wilson RD, Huang SJ, McLean AS. The correlation between airborne methicillin-resistant *Staphylococcus aureus* with the presence of MRSA colonized patients in a general intensive care unit. Anaesth Intensive Care 2004;32:202-9.
21. Boyce JM, Potter-Bynoe G, Chenevert C, King T. Environmental contamination due to methicillin-resistant *Staphylococcus aureus*: possible infection control implications. Infect Control Hosp Epidemiol 1997; 18:622-7.
22. Kluytmans J, van Belkum A, Verbrugh H. Nasal carriage of *Staphylococcus aureus*: epidemiology, underlying mechanisms, and associated risks. Clin Microbiol Rev 1997;10:505-20.
23. Sands KEF, Goldmann DA. Epidemiology of *Staphylococcus* and group A streptococci. In: Bennett JV, Brachman PS, editors. Hospital infections. 4th ed. Philadelphia: Lippincott Raven; 1998.
24. Rhame FS. The inanimate environment. In: Bennett JV, Brachman PS, editors. Hospital infections. 4th ed. Philadelphia: Lippincott Raven; 1998.
25. Lundholm IM. Comparison of methods for quantitative determinations of airborne bacteria and evaluation of total viable counts. Appl Environ Microbiol 1982;44:179-83.
26. Noble WC. Dispersal of microorganisms from skin. In: Noble WC, editor. Microbiology of human skin. 2nd ed. London: Lloyd-Luke Ltd; 1981. p. 79-85.
27. Williams RE. Epidemiology of airborne staphylococcal infection. Bacteriol Rev 1966;30:660-74.
28. Solberg CO. Spread of *Staphylococcus aureus* in hospitals: causes and prevention. Scand J Infect Dis 2000;32:587-95.
29. Kumari DN, Haji TC, Keer V, Hawkey PM, Duncanson V, Flower E. Ventilation grilles as a potential source of methicillin-resistant *Staphylococcus aureus* causing an outbreak in an orthopaedic ward at a district general hospital. J Hosp Infect 1998;39:127-33.
30. Wagenvoort JH, Davies BI, Westermann EJ, Werink TJ, Toenbreker HM. MRSA from air-exhaust channels. Lancet 1993;341:840-1.
31. Cotterill S, Evans R, Fraise AP. An unusual source for an outbreak of methicillin-resistant *Staphylococcus aureus*. J Hosp Infect 1996;32: 207-16.
32. Jawad A, Seifert H, Snelling AM, Heritage J, Hawkey PM. Survival of *Acinetobacter baumannii* on dry surfaces: comparison of outbreak and sporadic isolates. J Clin Microbiol 1998;36:1938-41.
33. Wagenvoort JHT, Joosten EJAJ. An outbreak of *Acinetobacter baumannii* that mimics MRSA in its environmental longevity. J Hosp Infect 2002; 52:226-7.

34. Jawad A, Snelling AM, Heritage J, Hawkey PM. Exceptional desiccation tolerance of *Acinetobacter radioresistens*. J Hosp Infect 1998;39: 235-40.
35. Allen KD, Green HT. Hospital outbreak of multi-resistant *Acinetobacter anitratus*: an airborne mode of spread? J Hosp Infect 1987; 9:110-9.
36. Das I, Lambert P, Hill D, Noy M, Bion J, Elliott T. Carbapenem-resistant *Acinetobacter* and role of curtains in an outbreak in intensive care units. J Hosp Infect 2002;50:110-4.
37. Houang ET, Chu YW, Leung CM, Chu KY, Berlau J, Ng KC, et al. Epidemiology and infection control implications of *Acinetobacter* spp in Hong Kong. J Clin Microbiol 2001;39:228-34.
38. Gerner-Smidt P. Endemic occurrence of *Acinetobacter calcoaceticus biovar anitratus* in an intensive care unit. J Hosp Infect 1987;10: 265-72.
39. Thornton T, Fletcher LA, Beggs CB, Elliott MW, Kerr KG. Airborne microflora in a respiratory ward. Presented at the ASHRAE IAQ Conference, Tampa, FL, March 15–17, 2004.
40. Obbard JP, Fang LS. Airborne concentrations of bacteria in a hospital environment in Singapore. Water, Air, and Soil Poll 2003;144:333-41.
41. Augustowska M, Dutkiewiez J. Variability of airborne microflora in a hospital ward within a period of one year. Ann Agric Environ Med 2006;13:99-106.
42. Kerr KG, Beggs CB, Dean SG, Thornton J, Donnelly JK, Todd NJ, et al. Air ionisation and colonization/infection with methicillin-resistant *Staphylococcus aureus* and *Acinetobacter* species in an intensive care unit. Intensive Care Med 2006;32:315-7.
43. Malamou-Ladas H, O'Farrell S, Nash JQ, Tabaqchali S. Isolation of *Clostridium difficile* from patients and the environment of hospital wards. J Clin Pathol 1983;36:88-92.
44. Hota B. Contamination, disinfection, and cross-colonization: are hospital surfaces reservoirs for nosocomial infection? Clin Infect Dis 2004;39:1182-9.
45. Fawley WN, Wilcox MH. Molecular epidemiology of endemic *Clostridium difficile* infection. Epidemiol Infect 2001;126:343-50.
46. Samore MH, Venkataraman L, DeGirolami PC, Arbeit RD, Karchmer AW. Clinical and molecular epidemiology of sporadic and clustered cases of nosocomial *Clostridium difficile* diarrhea. Am J Med 1996; 100:32-40.
47. Fekety R, Kim KH, Batts DH, Browne RA, Cudmore MA, Silva J Jr, et al. Studies on the epidemiology of antibiotic-associated *Clostridium difficile* colitis. Am J Clin Nutr 1980;33(11 Suppl):2527-32.
48. Fawley WN, Freeman J, Wilcox MH. Evidence to support the existence of subgroups within the UK epidemic *Clostridium difficile* strain (PCR ribotype 1). J Hosp Infect 2003;54:74-7.
49. Kim KH, Fekety R, Batts DH, Brown D, Cudmore M, Silva J Jr, et al. Isolation of *Clostridium difficile* from the environment and contacts of patients with antibiotic-associated colitis. J Infect Dis 1981;143: 42-50.
50. Fekety R, Kim KH, Brown D, Batts DH, Cudmore M, Silva J Jr. Epidemiology of antibiotic-associated colitis; isolation of *Clostridium difficile* from the hospital environment. Am J Med 1981;70:906-8.
51. Greene VW, Vesley D, Bond RG, Michaelsen GS. Microbiological contamination of hospital air, II: qualitative studies. Appl Microbiol 1962; 10:567-71.
52. Greene VW, Vesley D, Bond RG, Michaelsen GS. Microbiological contamination of hospital air, I: quantitative studies. Appl Microbiol 1962; 10:561-6.
53. Roberts K, Hathway A, Fletcher LA, Beggs CB, Elliott MW, Sleigh PA. Bioaerosol production on a respiratory ward. Indoor Built Environ 2006;15:35-40.
54. Roberts K, Smith CF, Snelling AM, Kerr KG, Banfield K, Sleigh PA, et al. Aerial dissemination of *Clostridium difficile*. Submitted to the BMC Infectious Diseases; 2007.
55. Kosar D. The answer is 3. Engineering Systems 2002;60-70.
56. Noakes CJ, Beggs CB, Sleigh PA. Modelling the performance of upper room ultraviolet germicidal irradiation devices in ventilated rooms: comparison of analytical and CFD methods. Indoor Built Environ 2004;13:477-88.
57. Zhao B, Zhang Y, Li X, Yang X, Huang D. Comparison of indoor aerosol particle concentration and deposition in different ventilated rooms by numerical method. Building Environ 2004;39:1-8.
58. Tang JW, Li Y, Eames I, Chan PKS, Ridgway GL. Factors involved in the aerosol transmission of infection and control of ventilation in healthcare premises. J Hosp Infect 2006;64:100-14.
59. Qian H, Li Y, Nielsen PV, Hyldgaard CE, Wong TW, Chwang AT. Dispersion of exhaled droplet nuclei in a two-bed hospital ward with three different ventilation systems. Indoor Air 2006;16:111-28.
60. Noakes CJ, Sleigh PA, Escombe AR, Beggs CB. Use of CFD analysis in modifying a TB ward in Lima, Peru. Indoor Built Environ 2006;15:41-7.
61. Beggs CB, Kerr KG, Snelling AM, Sleigh PA. *Acinetobacter* spp and the clinical environment. Indoor Built Environ 2006;15:19-24.
62. Philips D, Sinclair RJ, Schulyer GD. Isolation room ventilation design case studies. Presented at the ASHRAE IAQ Conference, Tampa, FL, March 15–17, 2004.
63. Memarzadeh F, Jiang J. Methodology for minimizing risk from airborne organisms in hospital isolation room. ASHRAE Trans 2000;106: MN-00-11-02.
64. Memarzadeh F, Manning A. Thermal comfort, uniformity, and ventilation effectiveness in patient rooms: performance assessment using ventilation indices. ASHRAE Trans 2000;106: MN-00-11-03.
65. Li Y, Leung GM, Tang JW, Yang X, Chao CY, Lin JZ, et al. Role of ventilation in airborne transmission of infectious agents in the built environment: a multidisciplinary systematic review. Indoor Air 2007;17:2-18.

Far UVC light for reducing airborne transmission of bacteria and viruses

Final report for NHS Scotland Assure

Project AssureResearch 21-0001

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Contents

1 Executive Summary

This study has carried out experimental measurements in a room scale chamber and computational fluid dynamics modelling to evaluate the performance of filtered Krypton-Chloride (KrCl) lamps (known as Far-UVC technology) in reducing the concentration of microorganisms in air and on surfaces in indoor settings. The study considers a range of microorganisms and ventilation conditions. Key findings from the study are:

- Far-UVC effectively inactivates airborne microorganisms in a room under controlled experimental conditions and under a range of ventilation rates.
- Far-UVC appears to result in inactivation of microorganisms on surfaces in the room at different ventilation rates.
- Far-UVC is very likely to inactivate airborne pathogens that are relevant to healthcare settings.
- The results from our preliminary work (Eadie et al. 2022) are robust to changes in ventilation pattern and sample location.
- The experimentally measured effectiveness increases with the number of lamps used and hence the quantity of Far-UVC in the room.
- A situation where the Far-UVC field is evenly distributed across a room demonstrates less variability than having the UVC source at a single location
- The optimum number of lamps with diffuser per unit volume could be as low as a single 15 W lamp per 8 m^3; our computer modelling suggests 4 lamps may have produced results very similar to the 5 lamps used within the chamber study. This would need to be explored with further experiments.
- The aim would be to optimise inactivation of pathogen for the lowest possible electrical power consumption. Our results provide guidance with current lamp wall plug efficiency, which is approximately 0.5% - 1%, i.e. a 15 W lamp produces somewhere between 0.075 - 0.15 W of Far-UVC.
- We have not measured health effects in this study, however our other ongoing work and international evidence has not identified any acute effects from filtered KrCl lamps on either skin or eyes. Evidence from cell and animal

studies suggests that long-term Far-UVC exposure is unlikely to cause non-melanoma skin cancer.

- We have not directly considered usability and acceptability in this study, however our experience across ongoing studies suggests that the following are important to consider in further research and evaluation:
    - communication/consultation with staff and patients to gauge their understanding of Far-UVC and the potential benefits and any risks
    - Evaluation of product design and robustness to identify which lamps would be suitable for healthcare installation
    - Consideration of which spaces would be most suitable for installation. Although Far-UVC is considerably safer than other wavelengths of UV light, it would be important to consider who would be exposed for how long and whether there are any groups who could be more vulnerable/concerned by the use of Far-UVC
- Our study has shown that Far-UVC has a great deal of potential, however these are in controlled scenarios. There remain several research questions which would inform deployment:
    - We have considered two microorganisms in the timescale of this study, however it would be important to test against a wider range including fungi
    - Our experiments are carried out using aerosolisation of the microorganisms in distilled water, which does not fully represent the size range or composition of human respiratory aerosols. Absorption by proteins in human respiratory aerosols may affect the efficacy of Far-UVC.
    - We have not measured any impacts of the Far-UVC on indoor air chemistry and potential for the creation of any harmful by-products. International evidence suggests that this risk is very low, however it would be advantageous for further research to evaluate this possibility.

2 Introduction

Krypton-Chloride excimer lamps, known as Far-UVC, is a recently developed technology that uses ultraviolet (UV) light to inactivate microorganisms in indoor spaces. The approach aims to predominantly reduce concentrations of microorganisms in air and hence reduce transmission of respiratory pathogens, but there may also be some benefits in terms of surface contamination. Evidence from studies prior to this project, including our chamber experiments, suggests that Far-UVC is effective at inactivating microorganisms including the SARS-CoV-2 virus.

Far-UVC uses UV light with a wavelength of 222nm that is germicidal. Unlike other UVC wavelengths, evidence suggests that Far-UVC is much safer for human exposure with no evidence from studies that it harms skin or eyes when used within current guidance exposure values. Far-UVC therefore has significant potential to mitigate transmission of infection, particularly in spaces which are poorly ventilated.

This report details experimental studies carried out in a room-scale bioaerosol chamber and computational modelling using a CFD approach to evaluate the performance of Far-UVC for a number of relevant microorganisms under different ventilation conditions. We consider the impact of Far-UVC on both air and surface microbial contamination. The report uses our results together with data from other studies worldwide to outline the potential for application in healthcare and further research needs.

3 Experimental Methodology

The experimental study was designed to investigate a number of factors, including:

- Comparison of ventilation rates to understand the performance under different airflow conditions.
- Comparison of ventilation regimes to understand the performance under different air patterns.
- Spatial effectiveness of the Far-UVC system including sampling at locations close to the aerosol source to determine whether the devices can have any impact on close-range transmission.
- Variation in inactivation with different microbial species.

3.1 Aerobiology chamber and FAR-UVC lamps

Experiments were conducted in the controlled aerobiology chamber at the University of Leeds; the dimensions used were similar to a single-bed room at the hospital (32.25 m^3): 4.26m (L) x 3.36m (W) x 2.26m (H). The ventilation was HEPA filtered at the supply and the extract to provide contaminant-free inlet air and ensure safe discharge (**Figure 1**).

The room is designed to safely conduct controlled aerosol experiments. All experiments were carried out with no occupants in the room and with the ventilation operating under negative pressure for safety. The chamber is capable of ventilation rates between 1.5 and 12 Air Changes per Hour (ACH).

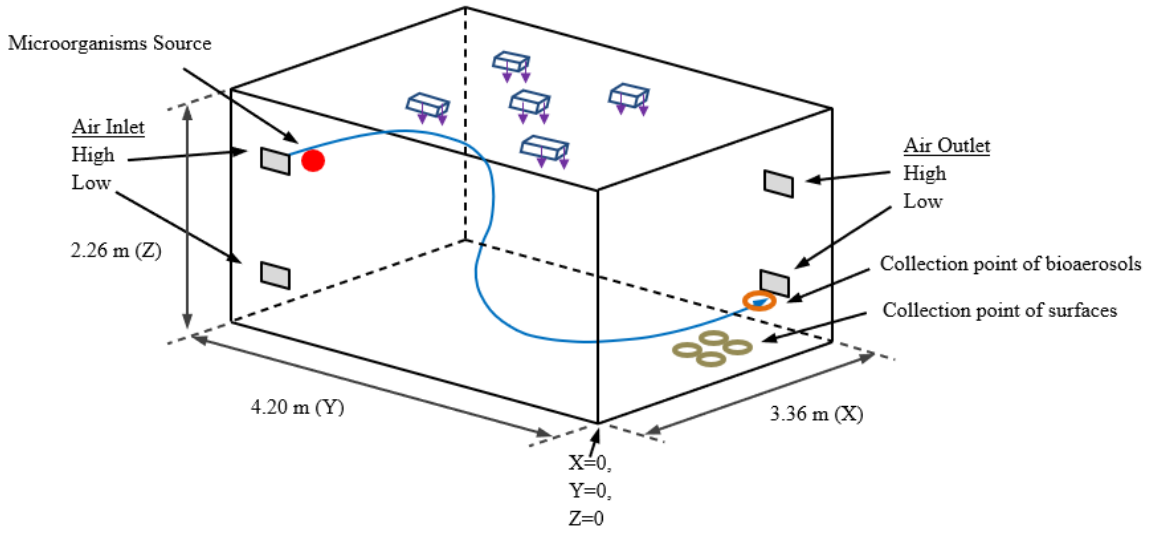

Figure 1: The aerobiological chamber dimensions and ventilation regime.

Prior to the microbial experiments, five Krypton Chloride excimer lamps were mounted close to the ceiling of the chamber in a quincunx formation. Filters were added so that the lamp intensity could be adjusted and diffusers were added to increase the volume of the room being irradiated. Experiments were carried out with one or five lamps operating. These Far-UVC devices are commercially available and have been donated to us by a company. We tested them with the lamps modified so they operate continuously at different power levels; this will allow us to test the technology rather than the product. This resulted in a room average UVC irradiance as reported in Eadie et al 2022 (see **Table 1**)

Table 1: Average irradiance and calculated 8-hour exposure dose for three different exposure conditions at two heights from the ground. The bold, italicised 8-hour exposure values are above the ICNIRP 222-nm exposure limit of 23 $mJcm^{-2}$. No exposures exceeded the 2022 ACGIH threshold limit value for skin of 478 $mJcm^{-2}$ at 222 nm.

	No. of lamps	Peak Values				Average Values			
		Height = 1.7 m		Height = 1 m		Height = 1.7 m		Height = 1 m	
		Irradiance (μWcm^{-2})	8-hour dose ($mJcm^{-2}$)	Irradiance (μWcm^{-2})	8-hour dose ($mJcm^{-2}$)	Irradiance (μWcm^{-2})	8-hour dose ($mJcm^{-2}$)	Irradiance (μWcm^{-2})	8-hour dose ($mJcm^{-2}$)
High	1	14.4	***415***	1.93	***56***	0.57	16.5	0.45	12.9
	5	14.4	***415***	3.42	***98***	2.73	***78***	2.01	***58***
Medium	1	0.92	***26.5***	0.13	3.7	0.03	0.87	0.03	0.82
	5	0.92	***26.5***	0.22	6.3	0.14	4.1	0.13	3.67
Low	1	0.09	2.65	0.01	0.37	0.003	0.09	0.003	0.08
	5	0.09	2.65	0.02	0.63	0.01	0.41	0.01	0.37

3.2 Preparation of culture broth, agar plates

A laboratory strain of *Staphylococcus aureus* (ATCC 6538) and *pseudomonas aeruginosa* (NCIMB 10848) culture was prepared by transferring a loopful of bacteria into a 100ml of sterilised nutrient broth (Oxoid Ltd, UK). This culture broth was then incubated at 37°C for 48 hours.

Tryptone Soya Agar (TSA) Oxoid Ltd, UK, was used to prepare Petri dishes plates 90 mm and 55 mm. An amount of 40g of TSA was added to one litre in the Masterclave 09 (Don Whitley Scientific). The agar mixtures were stirred for 15 minutes, and then they were heated to 121°C for 15 minutes. The agar was then cooled and left at a constant temperature of 45°C. An automated pourer stacker (Don Whitley Scientific) was used to pour the agar broth into sterile Petri dishes (37 ml/ Ø 90mm plate); this volume was recommended by (Mcdonagh et al., 2013). The TSA plates of Ø 55mm used in AMPAS were prepared using pouring methods. The manufacturer's instructions (Oxoid Ltd, UK) were followed to prepare the agar for 500ml of the medium in Duran bottles. The mixture was hand shaken to make sure it was thoroughly mixed; then, the agar was autoclaved at 121 °C for 15 minutes and later left to cool at 60 °C before pouring 20ml into the Ø 55mm Petri dishes under aseptic conditions. All the TSA plates of Ø 90mm and Ø 55mm agars were left to cool and become solid and then stored at room temperature to be used whenever required.

To find the concentration of the strain in the culture broth, it was diluted five folds (10^{-5} concentration) using serial dilutions with 9ml distilled water that was autoclaved at 121 °C for 15 minutes and left to cool before being used. 0.1ml of the fifth bottle was pipetted and dispensed on the TSA, then incubated at 37°C for 24h for counting. The concentration of the strain in the culture broth was (~1 x10^{8} cfu/ml).

3.3 Generation of the aerosolised microorganisms

The Collison 6-jet nebuliser (BGI, USA) was used to generate the aerosolised microorganisms in the range of 0.3-10 µm diameter (King et al., 2013). This nebuliser was operating at 12 L.min^{-1} and was located outside the chamber (**Figure 2**).

Figure 2: The suspension fluid in the Collison nebuliser.

These aerosolised microorganisms are released at one of three locations at coordinates (X,Y, Z) as shown in **Figure 1.**

- L_{G1}: Through a tube and near the high-level supply of fresh air (0.5 m, 3.55 m, 1.7 m).
- L_{G2}: Through a tube and near the middle Far-UVC lamp (0.68 m, 2.1 m, 1.7 m).
- L_{G3}: Through a hole in the wall directly to the centre of the long wall of the chamber (0 m, 2.1 m, 1.2 m).

The location of the source points (L_{G1}) has been used previously and was selected for the majority of experiments as it was not located directly under a Far-UVC source (Eadie et al., 2022). Location L_{G2} was chosen to be 2 m away from the collection point and Far-UVC was in the middle. Location L_{G3} was used to release *Pseudomonas aeruginosa* as it was challenging to create sufficient aerosol in the room (extremely low generation) and this location prevented losses in tubing that are present with other release locations.

The suspension fluid inside the Collison nebuliser vessel was created by adding 1ml from the culture broth, then adding it to 99 ml distilled water to achieve a concentration of (~1 $x10^6$ cfu/ml).

3.4 Air sampling

The bioaerosols were collected onto TSA using the 6-stage Anderson air sampler that was operated at a flow-rate of 28 $l.min^{-1}$ for one to ten minutes depending on the concentration inside the chamber to reach a raw colony count between 50-150 per plate as recommended (Cantium Scientific Limited, 2015). A correction table (Appendix B - 400 Hole Count) was used to apply positive hole correction for the air samples to correct for potential over-counting under higher bioaerosol concentrations (Cantium Scientific Limited, 2015). These six stages represent the lungs and allow different ranges of particles' size to go through (7, 4.7, 3.3, 2.1, 1.1 and 0.65 µm diameter). We used one plate for sampling from stage number 6 (0.65 µm diameter) because it represents more than 95% of the data, according to our observation. The sampler was located externally to the chamber in the ante-room, and air samples were taken using tubes via a sampling port at one of these three locations at coordinates (X,Y, Z) as shown in **Figure 1.**

- L_{A1}: Near the low air extract (2.85 m, 0.65 m, 0.5 m).
- L_{A2}: Near the high air extract (2.85 m, 0.65 m, 1.7 m).
- L_{A3}: Through a tube and near the middle Far-UVC lamp (2.68 m, 2.1 m, 1.7 m).

The location of the collection points (L_{A1} and L_{A2}) has been shown previously to be representative of the average bioaerosol concentration of the whole chamber. Location L_{A3} was chosen to present a social distance of 2 m away from the source of infection (L_{G3}) with the Far-UVC lamp in between L_{G3} and LA_3.

3.5 Surface Sampling

The deposited microorganisms were collected using a custom Automated Multiplate Passive Air Sampling (AMPAS) device (Hiwar et al., 2020). The device comprises a series of 6 Petri dishes arranged in a circle, covered by a rotating tray controlled by a stepper motor (**Figure 3**). The device is programmed to expose each agar plate to the microorganisms in the air at pre-determined times and for pre-programmed periods before covering them, without human intervention, to ensure they are no longer exposed to air. Four AMPAS devices were put close together in front of the outlet grid **Figure 1**.

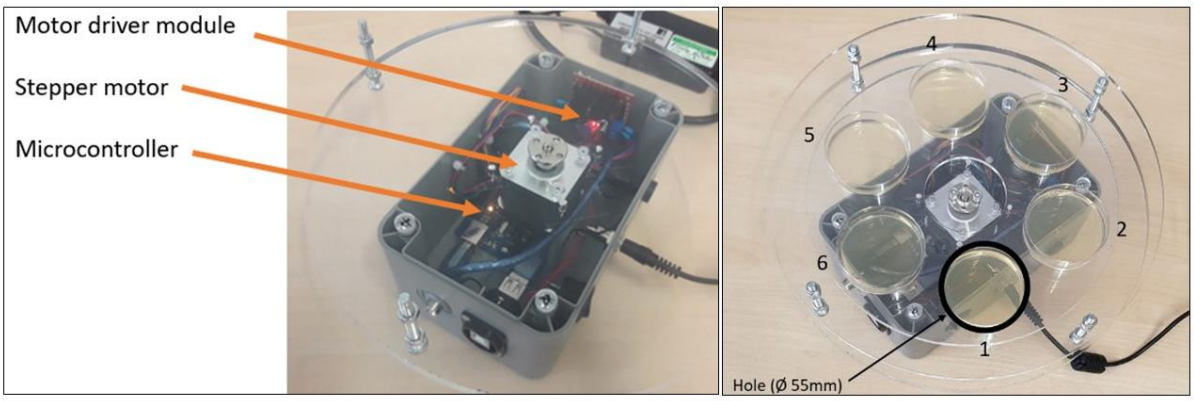

Figure 3: AMPAS device and components.

3.6 Experiments setting

All experiments were carried out under the steady-state conditions and under a slight negative pressure (0.5 bar) using between 1 and 5 ceiling-mounted Far-UVC lamps (Eadie et al., 2022). Prior to performing the microbial tests, we measured ventilation rates in the chamber using a Balometer. *Staphylococcus aureus* (gram-positive)/spherical shaped) was used in all experiments, while *Pseudomonas aeruginosa* (gram-negative)/rod shaped) was only used for the comparison of different species.

In each experiment, the nebuliser and ventilation operated continuously; this replicates a realistic scenario in a hospital setting where an infectious person is continuously releasing a pathogen over a long period of time. A continuous release of aerosolised microorganisms was introduced to the chamber for 210 minutes. The first 60 minutes were employed to let the room achieve steady-state conditions, then 50 minutes were used to perform sampling ten times (Far-UVC device off). The device(s) were then turned on and left for 20 minutes before taking ten more samples (Far-UVC device on) for 50 minutes. For air sampling, the duration time of sampling was 1-5 minutes (according to the type of experiment), and for surface sampling, it was in 10-minute cycles and was repeated five times (ten plates with Far-UVC device off and ten plates with Far-UVC device on). Following sampling, the nebuliser and Far-UVC devices were switched off, and the room ventilation rate was increased to 12 ACH for 30 minutes to flush any remaining airborne microorganisms from the room (**Figure 4**). Following the experiment, the plates were incubated at 37 °C for 24 hours.

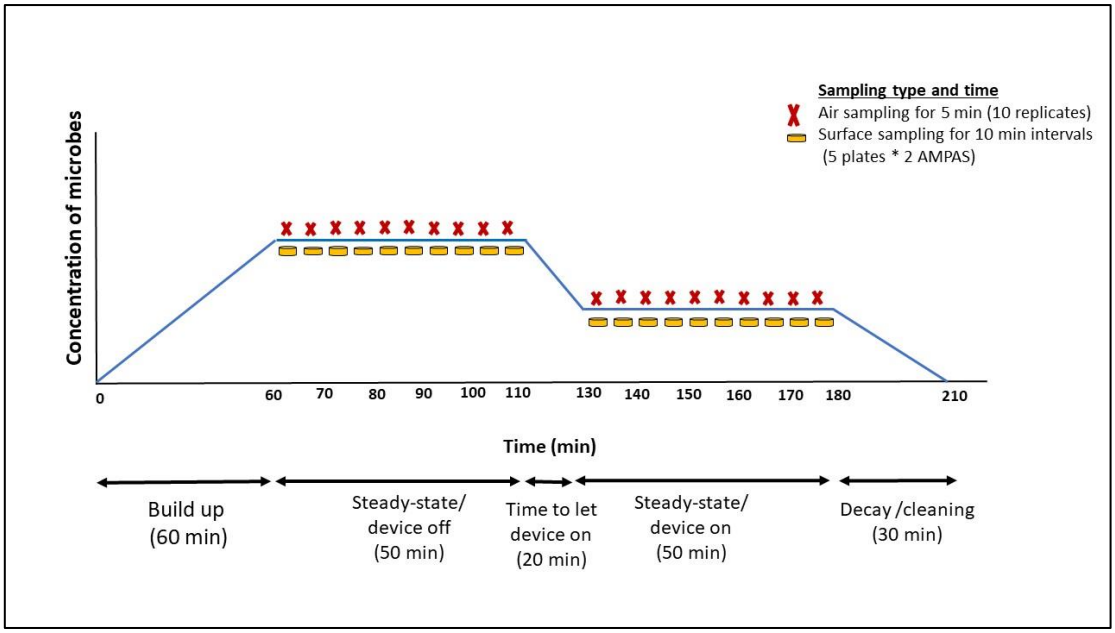

Figure 4: The microbial concentration with different sampling types and times.

Ventilation rate comparison was carried out at an airflow rate of 0.013 m^3s^{-1}, 0.027 m^3s^{-1}, 0.054 m^3s^{-1} and 0.081 m^3s^{-1} equivalent to 1.5, 3, 6 and 9 air-changes-per-hour (ACH), respectively, with the ventilation regime (high grid inlet- low grid outlet). The location of generation sources was $L_{G1,}$ and the collection point of air sampling was L_{A1}.

Ventilation regime comparison was carried out at high grid inlet- low grid outlet and low grid inlet- high grid outlet at a constant ventilation rate of 3 ACH. The location of generation sources was $L_{G1,}$ and the collection points of air sampling were L_{A1} and L_{A2}.

Spatial comparison was carried out at high grid inlet- low grid outlet at 3 ACH. The location of the generation source was $L_{G2,}$ and the collection points of air sampling were L_{A1} and L_{A3}.

Microbial species comparison was carried out with *Staphylococcus aureus* and *Pseudomonas aeruginosa* at 3 ACH with high grid inlet- low grid outlet. The location of generation source was L_{G1} (*Staphylococcus aureus*) and L_{G3} (*Pseudomonas aeruginosa*), and the collection point of air sampling was L_{A1}. Experiments were also attempted using Phi-6, a bacteriophage which is widely used as a surrogate for viruses, however these were not successful as it was not possible to generate a sufficient concentration in air to reliably measure the impact of the Far-UVC lamps.

4 Experimental Results

4.1 Ventilation rate comparison

The impact of using Far-UVC light on reducing the bioaerosols load under the steady state condition has been investigated at different ventilation rates. The concentration of bioaerosols was significantly lower with the Far-UVC light on, in all the experiments (See **Table 2** and **Figure 5**).

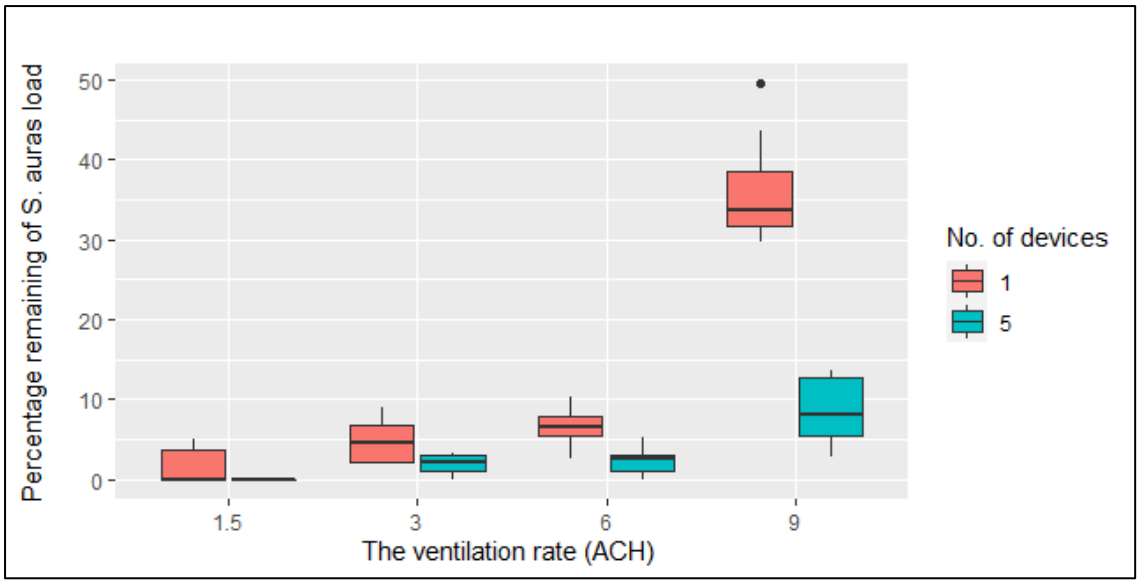

Figure 5: The performance of Far-UVC (222 nm) irradiation in reducing the concentration of *S. aureus* in the air under the steady state condition at different ventilation rates.

Table 2 and **Figure 5** illustrate that the Far-UVC devices have a significant impact on steady state reduction of microorganisms across a wide range of ventilation rates in the chamber. As expected, the relative benefit of the Far-UVC is greater at a lower ventilation rate and with a greater number of devices. At a high ventilation rate, there is already significant removal of microorganisms by the ventilation air, and hence the additional benefit measured by the experiments is relatively less than at a low ventilation rate. In addition, at a higher ventilation rate, the airflow in the room is at a higher velocity and will have a lower residence time within the UVC field.

Table 2: The performance of Far-UVC light to reduce the steady state concentration of airborne microorganisms at different ventilations rates. Lamp irradiance was "High" (see **Table 1**).

No. of devices	Far-UVC light (222 nm)	Ventilation rate (ACH)	Bioaerosols load (cfu/m3), Mean ± SD (Min-Max)	% Reduction			Experiment Resolution
				Median	LOG	IQR	
1	Off	1.5	711 ± 162 (536 - 1071)				
		3	1711 ± 391 (1286 - 2393)				
		6	800 ± 180 (583 - 1000)				
		9	1800 ± 313 (1357 - 2286)				
	On	1.5	11 ± 17 (0 - 36)	100%		-	5.4%
		3	75 ± 32 (36 - 143)	95.5%	1.35	93.3% - 97.8%	2.2%
		6	58 ± 21 (24 - 95)	92.8%	1.14	91.4%-93.9%	1.3%
		9	650 ± 124 (536 - 893)	66.3%	0.47	61.4% - 68.3%	2.0%
5	Off	1.5	2456 ± 388 (1702 - 2845)				
		3	3339 ± 424 (2714 - 4000)				
		6	1167 ± 99 (1036 - 1357)				
		9	1486 ± 479 (893 - 2250)				
	On	1.5	0 ± 0 (0 - 0)	100%			0.5%
		3	64 ± 38 (0 - 107)	97.8%	1.67	97.0% - 98.9%	1.1%
		6	27 ± 14 (0 - 54)	97.4%	1.58	96.8% - 98.8%	1.0%
		9	114 ± 54 (36 - 179)	91.9%	1.09	87.2% - 94.6%	2.7%

Table 3 shows the impact of the Far-UVC on the deposition rate of microorganisms under different ventilation rates. The impact of Far-UVC on reducing the load appears to be significant. However, the concentration of deposited microorganisms was low even when the Far-UV light was off because the concentration of bioaerosols was low over the different experiments. The relationship between the concentration of microorganisms in the air and on surfaces appears to be positively correlated; at a high ventilation rate (9 ACH), the deposition rate appears to be higher than at other flow rates, which may be due to the more dynamic airflow. The low concentrations mean that these results are close to the experimental resolution and further investigation is required with a higher concentration of bioaerosols to ensure that the collection of deposited microorganisms is sufficient in order to confirm this conclusion.

Table 3: The performance of Far-UVC light to reduce the concentration of deposited microorganisms on surfaces at different ventilation rates.

No. of device	Far-UVC light (222 nm)	Ventilation rate (ACH)	Deposited microorganisms concentration (cfu/plate*), Mean ± SD (Min-Max)	% Reduction			Experiment Resolution
				Median	LOG	IQR	
1	Off	1.5	0.30 ± 0.48 (0 - 1)				
		3	1.30 ± 1.16 (0 - 3)				
		6	0.20 ± 0.42 (0 - 1)				
		9	2.00 ± 1.25 (1 - 5)				
	On	1.5	0 ± 0 (0 - 0)	100.0%	-	-	-
		3	0 ± 0 (0 - 0)	100.0%	-	-	-
		6	0 ± 0 (0 - 0)	100.0%	-	-	-
		9	0.60 ± 0.97 (0 - 3)	100.0%	-	0.00% - 50%	50.0%
5	Off	1.5	0.50 ± 0.71 (0 - 2)				
		3	3.10 ± 2.02 (1 - 8)				
		6	1.40 ± 1.07 (0 - 3)				
		9	1.30 ± 1.25 (0 - 4)				
	On	1.5	0 ± 0 (0 - 0)	100.0%	-	-	-
		3	0.30 ± 0.48 (0 - 1)	100.0%	-	0.00% - 25%	33.3%
		6	0 ± 0 (0 - 0)	100.0%	-	-	50.0%
		9	0.20 ± 0.63 (0 - 2)	100.0%	-	-	100.0%

4.2 Ventilation regime

Different ventilation regimes were used and the impact of using Far-UVC light on reducing the bioaerosols load under the steady state conditions was investigated. The concentration of bioaerosols was significantly lower with the Far-UVC light on in all the experiments (See **Table 4** and **Figure 6**).

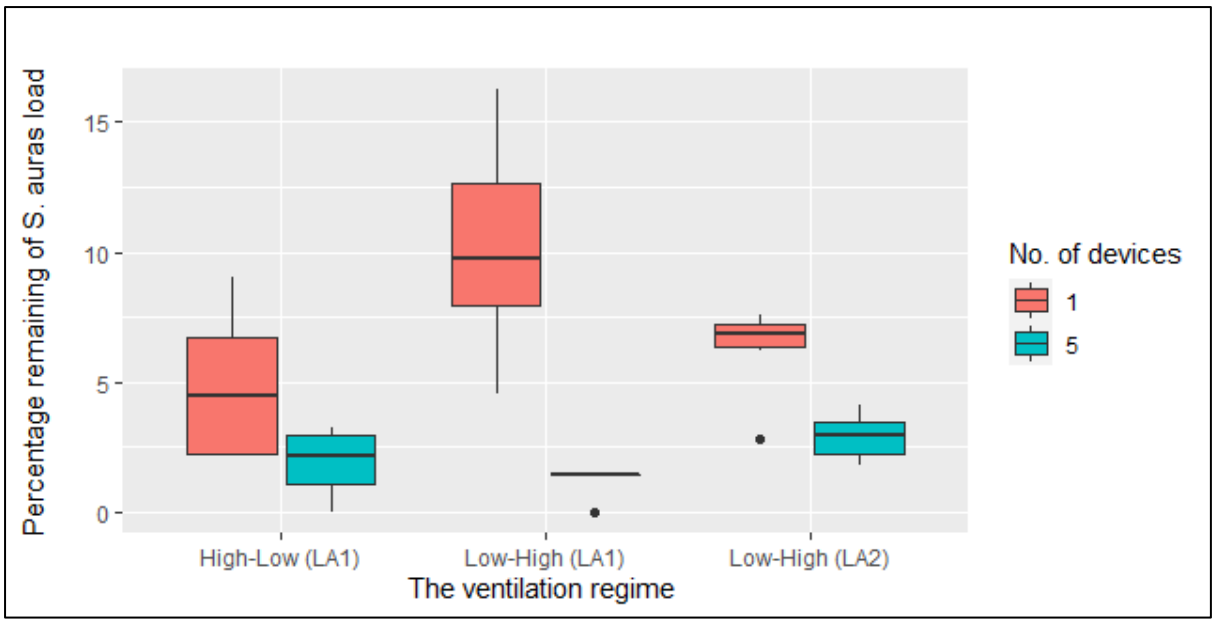

Figure 6: The performance of Far-UVC (222 nm) irradiation in reducing the concentration of *S. aureus* in the air at 3 ACH under different ventilation regimes.

As shown in **Table 4** and **Figure 6**, there is a small impact of ventilation regime and sample location on the reduction of microorganisms in the air. This is more noticeable in cases with only one lamp, where there is a greater variation in the results. The Far-UVC appears to be slightly more effective when the ventilation air is supplied from a high-level diffuser and extracted at low level, however there is not a clear pattern between ventilation regime and sample location seen in the results.

Table 4: The performance of Far-UVC light to reduce the concentration of airborne microorganisms under different ventilation regimes. Lamp irradiance was “High”.

No. of devices	Far-UVC light (222 nm)	Ventilation regime	Sampling point	% Reduction			Experiment Resolution
				Median	LOG	IQR	
1	Off	High-Low	L_{A1}: Near the low air extract (2.85 m, 0.65 m, 0.5 m).				
		Low-High	L_{A1}: Near the high air extract (2.85 m, 0.65 m, 0.5 m).				
		Low-High	L_{A2}: Near the high air extract (2.85 m, 0.65 m, 1.7 m).				
	On	High-Low	L_{A1}: Near the low air extract (2.85 m, 0.65 m, 0.5 m).	95.5%	1.35	93.3% - 97.8%	2.2%
		Low-High	L_{A1}: Near the high air extract (2.85 m, 0.65 m, 0.5 m).	90.3%	1.01	87.3% - 92.0%	0.6%
		Low-High	L_{A2}: Near the high air extract (2.85 m, 0.65 m, 1.7 m).	93.1%	1.16	92.8%-93.7%	0.3%
5	Off	High-Low	L_{A1}: Near the low air extract (2.85 m, 0.65 m, 0.5 m).				
		Low-High	L_{A1}: Near the high air extract (2.85 m, 0.65 m, 0.5 m).				
		Low-High	L_{A2}: Near the high air extract (2.85 m, 0.65 m, 1.7 m).				
	On	High-Low	L_{A1}: Near the low air extract (2.85 m, 0.65 m, 0.5 m).	97.8%	1.67	97.0% - 98.9%	1.1%
		Low-High	L_{A1}: Near the high air extract (2.85 m, 0.65 m, 0.5 m).	98.6%	1.85	-	1.4%
		Low-High	L_{A2}: Near the high air extract (2.85 m, 0.65 m, 1.7 m).	97.1%	1.53	96.5% - 97.8%	0.3%

4.3 Distance comparison

A social distance of 2 m away from the source of infection with the Far-UVC lamp located centrally between releasing and sampling points was investigated (**Figure 7**). This is compared to results with the same lamp but with the release and sample locations as in the scenarios above. Initial results to evaluate whether a Far-UVC device is effective at reducing exposure at different distances from the source suggest that even at closer proximity where the exposure time will be lower, the Far-UVC has a substantial effect (**Table 5** and **Figure 8**). However, experiments to measure the effect of proximity are challenging to set up and conduct, and more research is required to evaluate the influence of distance

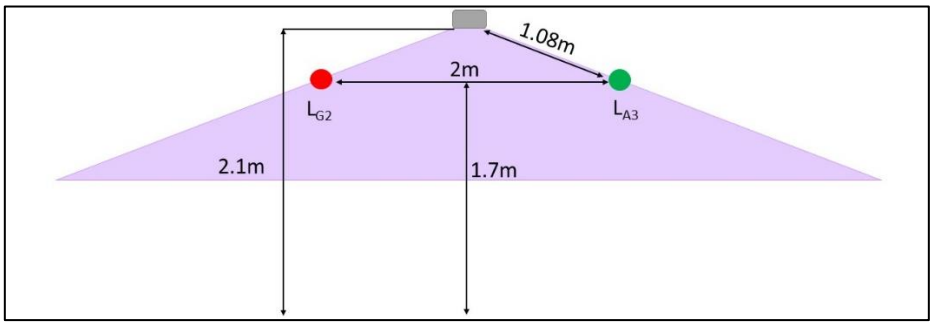

Figure 7: The short-range distances experiment setup showing source (L_{G2}), Far-UVC lamp and sample locations (L_{A3}).

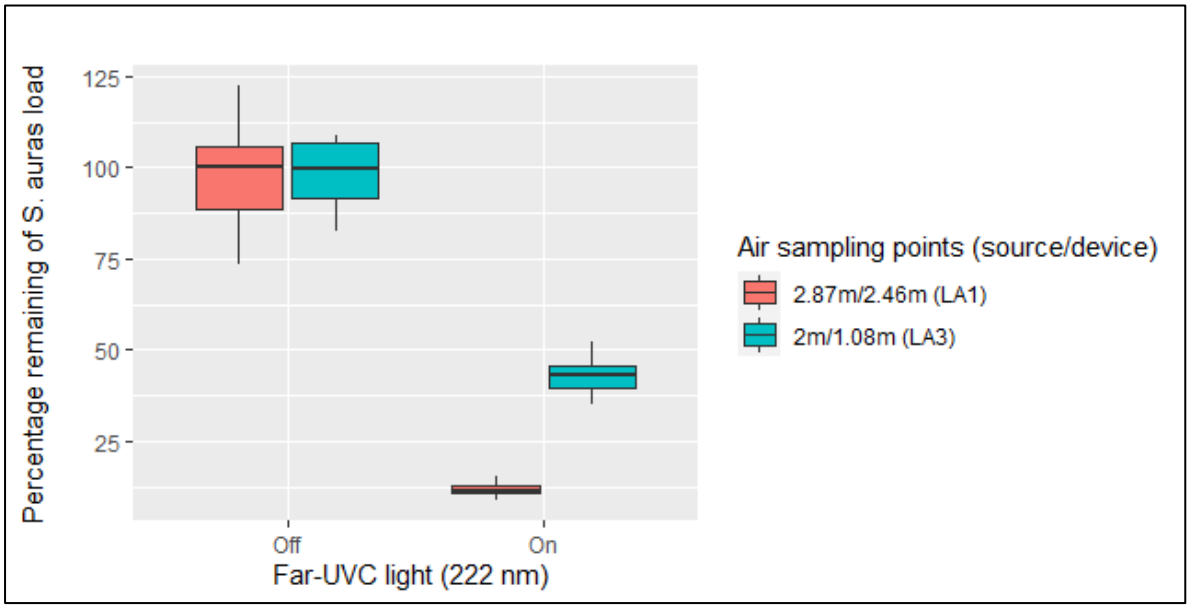

Figure 8: The performance of Far-UVC (222 nm) irradiation in reducing the concentration of *S. aureus* in the air at 3 ACH and at different distances between the source and sample location.

Table 5: The performance of one Far-UVC light device to reduce the concentration of airborne microorganisms at different distances between source and sample. Lamp irradiance was “High” (see **Table 1**).

Far-UVC light (222 nm)	Air sampling collection point	Bioaerosols load (cfu/m3), Mean ± SD (Min-Max)	% Reduction			Experiment Resolution
			Median	LOG	IQR	
Off	2m away from the source, 1.08m from the Far-UVC device (L_{A3}: Near the middle device [2.68 m, 2.1 m, 1.7 m])	2436 ± 227 (2054 - 2696)				
	2.87m away from the source, 2.46m away from the Far-UVC device (L_{A1}: Near the low air extract [2.85 m, 0.65 m, 0.5 m])	2348 ± 351 (1768 - 2946)				
On	2m away from the source, 1.08m from the Far-UVC device (L_{A3}: Near the middle device [2.68 m, 2.1 m, 1.7 m])	1045 ± 124 (857 - 1268)	57.4%	0.4	55.1% - 61.0%	0.7%
	2.87m away from the source, 2.46m away from the Far-UVC device (L_{A1}: Near the low air extract [2.85 m, 0.65 m, 0.5 m])	282 ± 44 (214 - 375)	88.5%	0.9	87.4%- 89.4.7%	0.7%

4.4 Microbial species

Two different microbial species (*Staphylococcus aureus* and *Pseudomonas aeruginosa*) were considered at 3 ACH with ventilation regime (high grid inlet- low grid outlet). The results show that for both species, the Far-UVC light had a significant impact on their inactivation (**Table 6** and **Figure 9**). It should be noted that

results for the two species need to be compared with caution as the release location was different for *Pseudomonas aeruginosa* due to experimental challenges.

Table 6: The performance of Far-UVC light to reduce the concentration of airborne microorganisms for different species. Lamp irradiance was “High” (see **Table 1**), mechanical ventilation was 3 ACH.

No. of device	Far-UVC light (222 nm)	Generation source	Species	Bioaerosols load (cfu/m3), Mean ± SD (Min-Max)	% Reduction			Experiment Resolution
					Median	LOG	IQR	
1	Off	L_{G1}: Through a tube and near the supply fresh air (0.5 m, 3.55 m, 1.7 m).	*SA*	1711 ± 391 (1286 - 2393)				
		L_{G3}: Through a hole in the wall directly to the chamber (0 m, 2.1 m, 1.2 m).	*PA*	567 ± 48 (507 - 657)				
	On	L_{G1}: Through a tube and near the supply fresh air (0.5 m, 3.55 m, 1.7 m).	*SA*	75 ± 32 (36 - 143)	95.5%	1.3	93.3% - 97.8%	2.2%
		L_{G3}: Through a hole in the wall directly to the chamber (0 m, 2.1 m, 1.2 m).	*PA*	31 ± 11 (14 - 50)	94.9%	1.3	93.6% - 94.9%	1.4%
5	Off	L_{G1}: Through a tube and near the	*SA*	3339 ± 424 (2714 - 4000)				

		supply fresh air (0.5 m, 3.55 m, 1.7 m).						
		L_{G3}: Through a hole in the wall directly to the chamber (0 m, 2.1 m, 1.2 m).	*PA*	471 ± 51 (345 - 524)				
	On	L_{G1}: Through a tube and near the supply fresh air (0.5 m, 3.55 m, 1.7 m).	*SA*	64 ± 38 (0 - 107)	97.8%	1.7	97.0% - 98.9%	1.1%
		L_{G3}: Through a hole in the wall directly to the chamber (0 m, 2.1 m, 1.2 m).	*PA*	2 ± 6 (0 - 12)	100.0%	-	-	2.5%

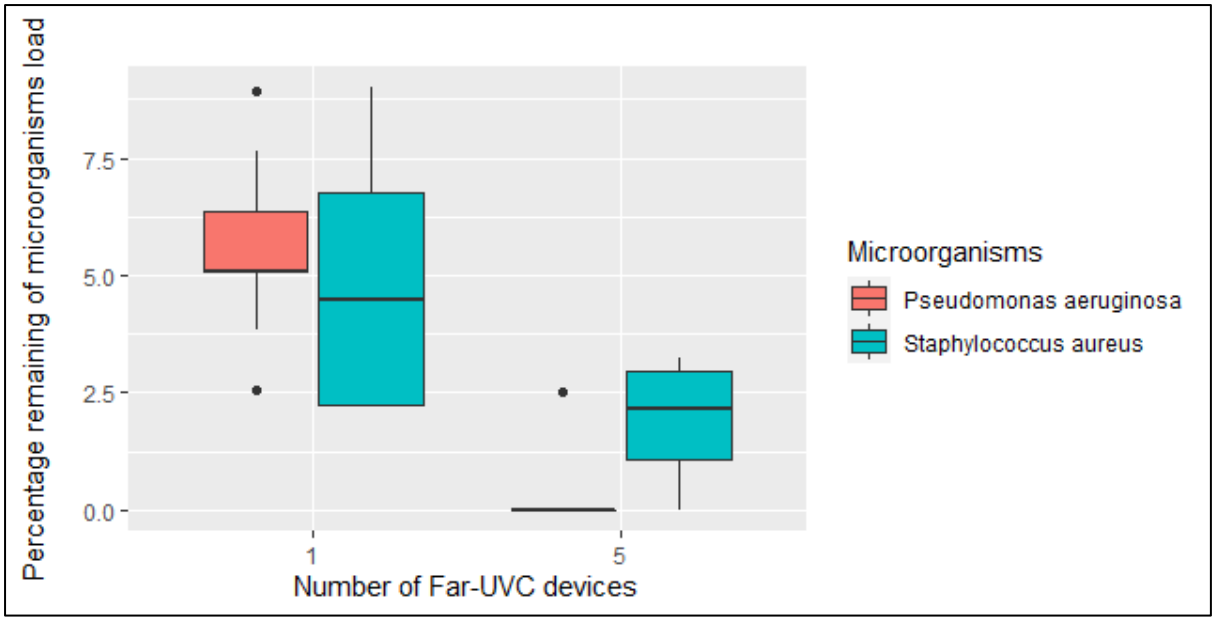

Figure 9: The performance of Far-UVC (222 nm) radiation in reducing the concentration of *S. aureus* and *P. aeruginosa* in the air at 3 ACH.

5 Computational Simulation Methodology

Complex computational simulations, designed to replicate the set-up above, were undertaken. Results of the simulations were compared to the experimental results for validation purposes and then the simulations were expanded to investigate variables which were not explored experimentally.

5.1 Steady state airflow and particle dissemination

To calculate the flow fields of the room we use the open source computational fluid dynamics (CFD) software package, OpenFOAM [OpenCFD Ltd] to calculate steady-state, incompressible solutions of the Reynolds-averaged Navier-Stokes equations.

The room dimensions are as described above, we use a uniform grid to model the room with a mesh resolution of 2cm, where the inlet and outlet are modelled as 25cm by 50cm patches. The inflow pattern modelled was taken from a previously measured velocity profile for the chamber, where we set the inflow velocity to achieve the required ACH.

As a result, we obtain a steady state airflow for different setups (**Figure 10**). Assuming that particles are held in aerosolised drops of liquid we can mimic the dispersal of bacteria or virus by using the steady state result. Particle dissemination is calculated by using Fluid Gravity Ltd's particle dissemination code to integrate the equations of motion for a particle moving through a gas, subject to drag and gravity. The simulations assume the limiting case of zero-radius particles, so the particles behave as passive tracers following the fluid flow. This is an appropriate assumption for the small aerosols used in the experimental study which largely move like a gas (Noakes et al 2009), however it is important to note that it may not be representative of larger respiratory aerosols that are more likely to deposit quickly.

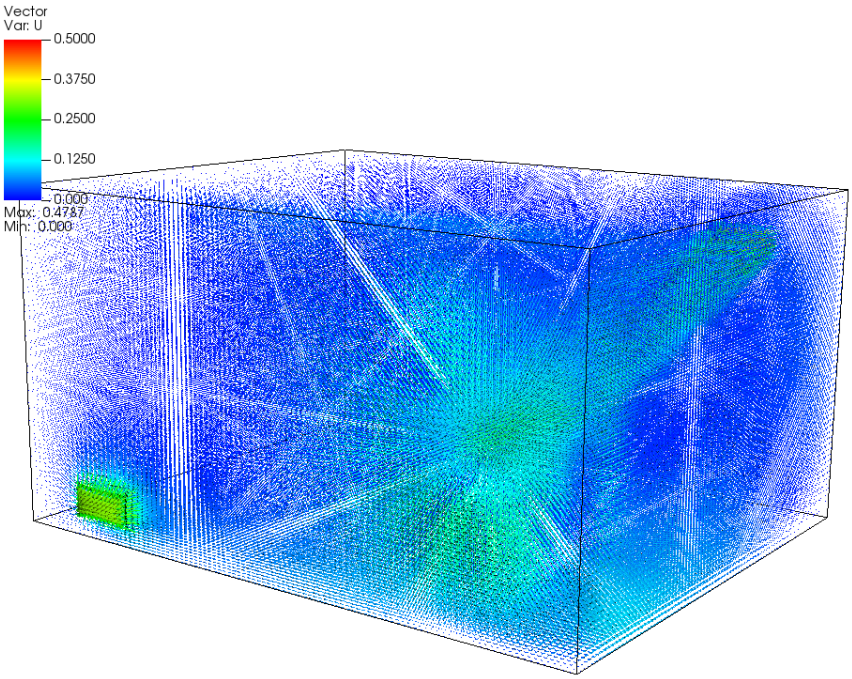

Figure 10: Airflow pattern of the chamber as produced by the CFD simulations

5.2 Far-UVC fluence rate

The three-dimensional fluence rates arising from the Far-UVC devices are computed throughout the room using a Monte Carlo radiation transfer (MCRT) code. To accurately model the pattern and fluence rate of the lamps the measured irradiance at heights of 1.7m and 1.0m from the ground are incorporated into the MCRT simulations which are scaled accordingly. Scattering and absorption are not considered within the room because the attenuation coefficient for Rayleigh scattering and absorption in air is of order 10^{-5} m^{-1} at 222nm and we assume a reflection coefficient of the chamber walls of 10% which is typical for common surfaces.

5.3 Pathogen Inactivation

To model the inactivation of any bacteria or viruses we combine the particle trajectories obtained with CFD and particle dissemination code with the Far-UVC illuminating patterns produced with the MCRT. One important assumption for this model to work is that the interaction between the Far-UVC and the pathogen is independent from the fluid dynamics.

As particles move within the flow field in the room they are exposed to a spatially varying fluence rate. We can describe the fluence rate as a function of position and time used then to compute the absorbed dose of each particle throughout its exposure to Far-UVC light in a one-time release. Assuming an exponential decay for the inactivation of the pathogen with a specific inactivation constant (k-value), we can then calculate the inactivation percentage of a given pathogen for any experimental setup. This follows the approaches used in previous studies modelling upper-room UV systems (Gilkeson and Noakes 2013). As mentioned previously, the measured results of the chamber experiment are from a continuous release of *S. aureus* that is regularly sampled every 5 minutes. The continuous release particles can be modelled using time-shifted copies of existing trajectories in the data set. For modelling *S. aureus* inactivation we use k-values of k = 3.6 cm^2mJ^{-1} and also adjust for the experimental sampling times recorded.

6 Computer Simulation Results

6.1 Model Validation

Figure 11 shows the simulations results (dashed lines) using a decay constant, k = 3.6 cm^2mJ^{-1} and experimental data for *S. aureus* (data points) plotted on a linear scale at ventilation rate of 3 ACH. Particles are continuously introduced into the chamber and the bacterial load builds up to a steady state. After two hours the lights are turned on and a new, lower steady state is attained.

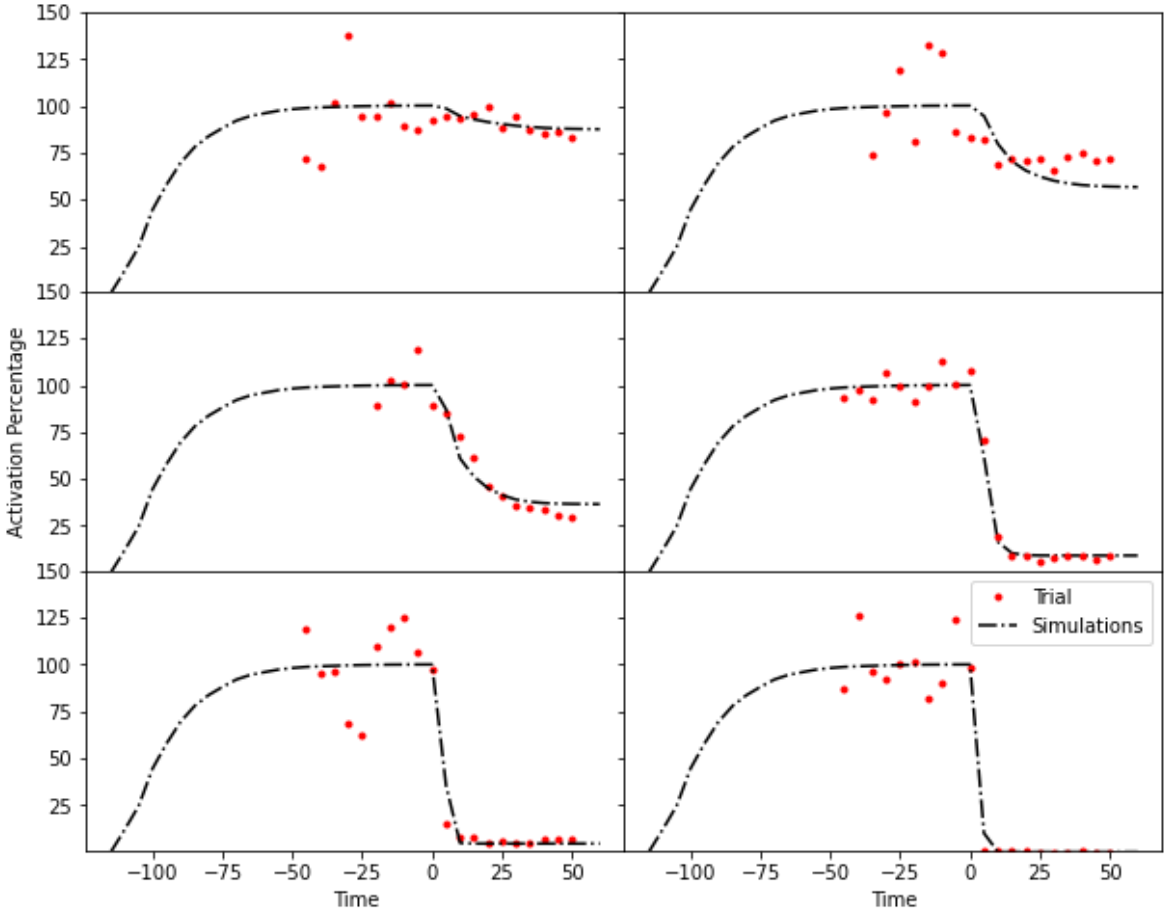

Figure 11: Simulations results compared to experimental results for 3 ACH. Left panels are for a single light and right panels for five lights, while the intensity settings of the lights are low (upper panels), medium (central panels), and high (lowest panels).

Results using k = 1.8 cm^{2}mJ^{-1} as estimated from the small-chamber experiments (assuming a single pass through a spatially uniform UVC radiation field) (REF) do not reproduce the measured level of bacterial inactivation within the larger bioaerosol chamber. However, a k value that is double (k = 3.6 cm^{2}mJ^{-1}) provides a better match between simulation and experimental result as can be seen in **Figure 11**. The increased k-values are required because the aerosolised particles take complex paths through the 3-Dimensional Far-UVC light pattern within the small and large chambers, meaning that simply assuming a single-pass through a spatially-uniform light pattern is not accurate. Previous studies of upper-room UV systems have also show that room scale inactivation constants differ from single-pass data (Beggs et al 2006).

Comparing the original experimental data with our simulations shows very good agreement between both data sets. We can observe the Far-UVC modelling can accurately account for the inactivation of *S. aureus* given different lighting patterns and intensities. Considering the costs and limitations of the experimental setup, this is an important validation of our models as it allows for the exploration of a much larger parameter space. More specifically we can explore what the ideal light setup is for a minimum inactivation of any pathogen in small aerosol given an appropriate inactivation rate constant, and therefore inform what the most cost-efficient solution is for wide implementation.

6.2 Different Pathogens

With the computer modelling validated, the simulation was repeated for human coronaviruses (HCOV) which have a higher k-value. Due to the higher sensitivity of human coronaviruses to Far-UVC (Eadie et al. 2022), the reduction in pathogen load in the room was predicted to be higher than with *S. aureus*, particularly at lower lamp intensities (**Table 7**).

Table 7: Modelled percentage reductions for different microorganisms and lamp configurations.

Lamp intensity	Number of lamps	Modelled S. aureus k = 3.6 cm^2mJ^{-1}	Modelled H. CoV k = 12.4 cm^2mJ^{-1}
Low	1	19.1%	34.4%
	5	56.6%	75.6%
Medium	1	74.3%	86.7%
	5	93.5%	96.6%
High	1	95.4%	99.1%
	5	99.8%	99.99%

6.3 Different ventilation rate

Like **Figure 11, Figure 12** shows the simulations (dashed lines) and experimental data for (data points) on a linear scale where left panels are for a single light and right panels for five lights at a high intensity setting. In this case each row shows the results for ventilation rates of 1.5 ACH, 3ACH, 6ACH and 9 ACH in descending order.

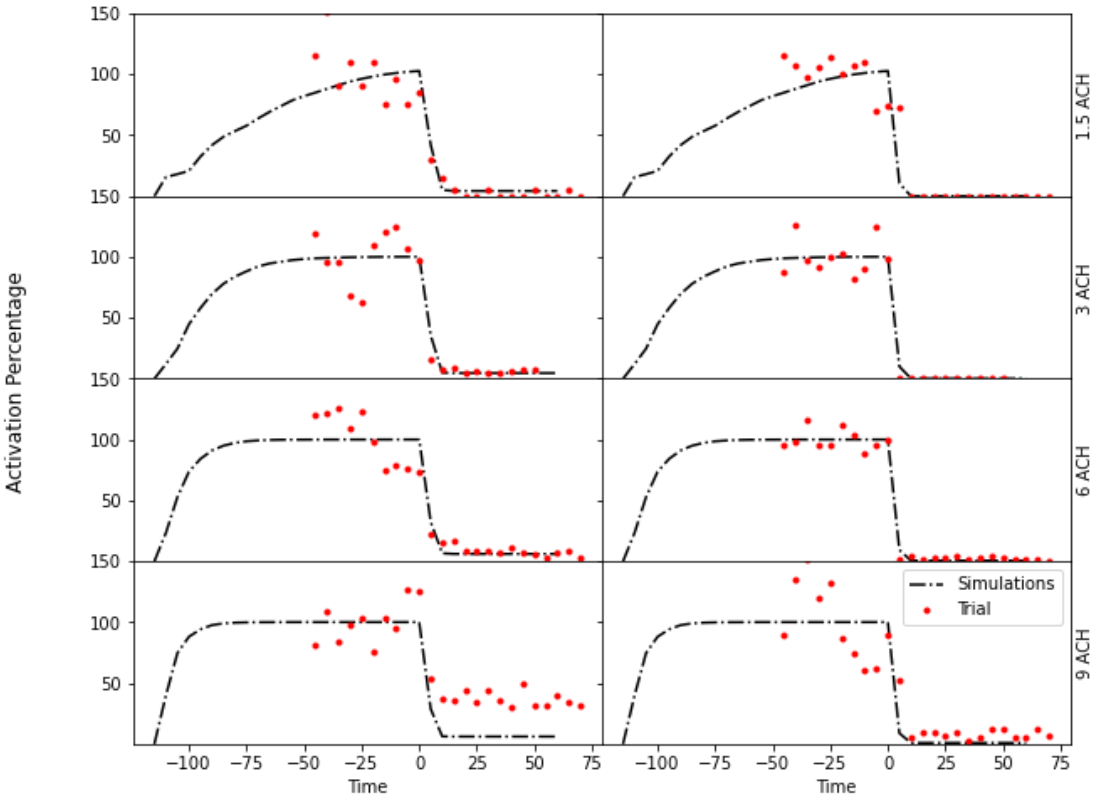

Figure 12: Model comparison with experimental data at different ACH.

6.4 Optimal Number of Lamps

Whilst the experimental work focussed on either one or five lamps, the computer modelling explored additional lamp numbers. **Figure 13** demonstrates diminishing returns, with incrementally less pathogen reduction as the number of lamps is increased. In the “Medium” scenario, equivalent to current UK exposure limits, four lamps has a percentage reduction that is within 2% of the reduction achieved by five lamps, I.e. approximately equal.

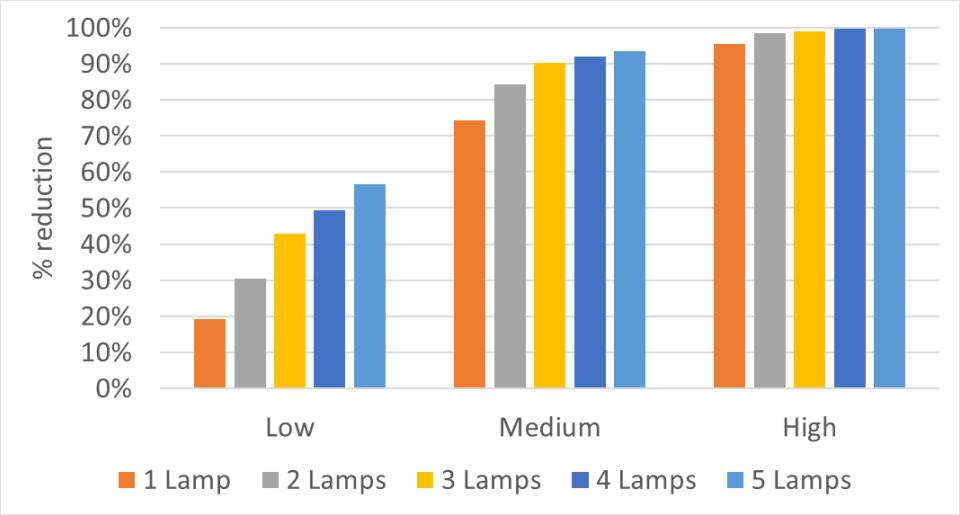

Figure 13: Percentage reduction in S. aureus, simulated by the computer modelling, for lamp numbers which were both tested (1 and 5 lamps) and not tested (2 and 4 lamps) experimentally. The modelling was performed with the Far-UVC lamp having diffused irradiation.

6.5 Lamps without a diffuser

Our previous research, modelling a classroom environment, indicated that if the Far-UVC lamps had diffusers, increased inactivation could be achieved with fewer lamps (Wood et al. 2021). In the environment of the bioaerosol chamber, there is an advantage in having diffusers on the lamps when there are fewer lamps or the lamps are of lower intensity (**Table 8**). The advantage of the diffusers decreases as the number of lamps and their intensity are increased.

Table 8: Simulated percentage reduction in S. aureus for Far-UVC lamps with, and without, diffusers. Room mechanical ventilation rate of 3 ACH.

	Low		Medium		High	
# Lamps	**Diffuser**	**No Diffuser**	**Diffuser**	**No Diffuser**	**Diffuser**	**No Diffuser**
1	19.1%	12.1%	74.3%	57.6%	95.4%	88.2%
2	30.5%	21.6%	84.3%	68.3%	98.5%	94.3%
3	42.9%	32.4%	90.2%	81.2%	99.0%	97.4%
4	49.4%	39.7%	92.1%	87.2%	99.6%	99.2%
5	56.6%	45.5%	93.5%	89.7%	99.8%	99.2%

6.6 Caveats and implementation

Results in **Figure 12** further validate the accuracy of our models showing a good correlation between simulations and experimental data at 1.5, 3 and 6 ACH. At 9 ACH our models are more efficient at the pathogen inactivation than the experimental results. It is worth noting that a comparative higher activation percentage at high ACH does not imply a higher pathogen load within the room. At higher ACH a lower overall pathogen load is to be expected, therefore the higher activation percentage indicates the relative efficiency of UVC sources at higher ACH.

Our approach to simulating the Far-UVC inactivation of *S. aureus* replicates the experimental results at relatively low ACH but overestimates the efficiency of Far-UVC at 9ACH. There are two possible explanations for the failure to accurately reproduce these results. First, our CFD models assume a steady-state airflow which is then used to describe the particle trajectories within the room. At higher ACH this might be too simplistic an approach leading to an inaccurate description of the particle trajectories and therefore its inactivation. Alternatively, the limitation might be in the simple approach to inactivation modelled as an exponential decay. Viruses and bacteria might require a more detailed inactivation function where the decay constant is dependent on exposure times; such a scenario would explain why our models overestimate the inactivation.

We have carried out several different simulations that accurately reproduce the experimental data measured. We find this provides a confident validation of our computer model and approach when used at ventilation rates equal to or lower than 6 ACH. Furthermore, this allows the exploration of a much larger parameter space beyond the technical limitations of an elaborate experimental setup.

7 Potential for Application of Far-UVC in Healthcare Settings

7.1 Equivalent Air Change Rates

Our experiments were all carried out under steady state conditions, whereby we compare the concentration of airborne microorganisms in the chamber with no Far-UVC with the concentration with the Far-UVC switched on, after allowing the room to reach steady state conditions. This is different to tests that many manufacturers use which measure the decay time with and without Far-UVC. A decay approach is more suited to when a device is used to remove contamination after an event (fallow time) and is commonly expressed as an equivalent ventilation rate, while the steady state methods in our study are used to replicate occupied spaces where the contamination of the environment can be considered to be continuous.

Although we have expressed results in terms of a % reduction under steady state conditions, this can be converted to an equivalent air change rate for the experimental set up.

Under steady state conditions with no Far-UVC and assuming the air in the chamber is well mixed, the concentration of microorganisms in air, C_{off} (cfu/m^3) is given by

$$C_{off} = \frac{q}{(N_v + N_d)V}$$

Here, q is the emission rate of microorganisms (cfu/hr), V is the volume of the room (m^3), N_v is the ventilation rate in air changes per hour (ACH), and N_d is the loss rate (1/hr) due to deposition and natural decay.

In the case where the Far-UVC is switched on, the new concentration, C_{uv} (cfu/m3) can be expressed as the combined effect of the room ventilation rate N_v plus an equivalent air change rate, N_{uv} (ACH)

$$C_{uv} = \frac{q}{(N_v + N_d + N_{uv})V}$$

In our experiments the fraction of microorganisms remaining when the Far-UVC is switched on is given by

$$\frac{C_{off}}{C_{uv}}$$

By substituting for C_{off} and C_{uv} in the above, assuming that deposition and natural decay remain the same regardless of the UV and ventilation rate, and rearranging, the equivalent ventilation rate due to the UV can be given by

$$N_{uv} = N\left(\frac{C_{off}}{C_{uv}} - 1\right)$$

Table 9 illustrates this theoretical relationship between reduction in air, the ventilation rate in the room and the calculated additional equivalent ventilation provided by the Far-UVC. Here we have indicated an approximate mapping to the experimental results in **Table 2**, where cells coloured yellow represent cases with a single lamp and cells coloured green represent cases with 5 lamps. At very low room ventilation rate (1.5 ACH), 100% reduction was seen in both cases; it is not possible to calculate an equivalent ventilation rate for this level of reduction so the orange cell indicates the calculated equivalent ventilation rate for a 99% reduction.

It should be noted that these air change rates relate to the experimental chamber which is a relatively small room. However, it can clearly be seen that very high equivalent ventilation rates are achievable with the Far-UV system. As a comparison, a typical HEPA based air cleaner with a Clean Air Delivery Rate between 150 and 300 m3/hr would deliver an equivalent additional ventilation rate of 4.7 to 9.4 ACH for the experimental chamber.

Table 9: Theoretical equivalent ventilation rate (ACH) for different room ventilation rates (ACH) and % reduction due to Far-UVC. Lamp irradiance “High” (see **Table 1**).

% Reduction	% Remaining	Nv	Nuv	Nv	Nuv	Nv	Nuv	Nv	Nuv
10	0.9	1.5	0.17	3	0.33	6	0.67	9	1.00
30	0.7	1.5	0.64	3	1.29	6	2.57	9	3.86
50	0.5	1.5	1.50	3	3.00	6	6.00	9	9.00
66	0.34	1.5	2.91	3	5.82	6	11.65	9	17.47
70	0.3	1.5	3.50	3	7.00	6	14.00	9	21.00
90	0.1	1.5	13.50	3	27.00	6	54.00	9	81.00
92	0.08	1.5	17.25	3	34.50	6	69.00	9	103.50
93	0.07	1.5	19.93	3	39.86	6	79.71	9	119.57
96	0.04	1.5	36.00	3	72.00	6	144.00	9	216.00
97	0.03	1.5	48.50	3	97.00	6	194.00	9	291.00
98	0.02	1.5	73.50	3	147.00	6	294.00	9	441.00
99	0.01	1.5	148.50	3	297.00	6	594.00	9	891.00

7.2 Electrical Power Requirements

The lamps used in the experimental and modelling studies have an electrical power consumption of 15 W. In the “Medium” scenario (see **Table 1**), which is roughly equivalent to current UK Far-UVC exposure limit legislation, an approximate **90% reduction in pathogen load could be achieved for an effective electrical power consumption of 2.3 W m^{-3} (5 lamps x 15 W / 32.25 m^3).** This is with a mechanical ventilation rate of 3 ACH, and as per **Table 7** would provide an equivalent additional ventilation rate of around 27 ACH.

The 2.3 W m^{-3} is somewhat of a worst-case scenario for several reasons:

First, in our experiments, in order to run the lamps continuously and comply with UK ultraviolet exposure limits, we had to attenuate the Far-UVC – effectively “wasting” useful UV. An alternative technique to remain within exposure limits is for the lamp to switch on and off on a duty cycle. In our experiments a duty cycle of 10% (1:9) would have been required to remain within UK exposure limits directly under a lamp. Duty cycling is the most common method utilised by Far-UVC suppliers and would result in an approximately **90% reduction in pathogen load for an average power consumption of approximately 0.23 W m^{-3}**. However this makes a few assumptions, one of the largest being that the same pathogen reduction would be achieved by duty cycle as is achieved by continuous operation. We have not investigated this experimentally as the duty cycle adds a further uncertainty into the experimental conditions, but our previous modelling based research (Wood et al. 2021) suggests it may not be the case and further investigation is required.

Secondly, we make the assumption that the exposure limit assumes a “worst-case” of an individual stood directly under the lamp for a full eight hours. However, this is not realistic and time-weighted studies have shown actual exposures to be between 20-50% of the “worst-case” scenario. Therefore, the lamp intensity could be increased whilst still complying with current exposure legislation, which will not improve the power consumption but would improve the pathogen reduction.

Thirdly the computer modelling suggests fewer lamps could achieve above 90% pathogen reduction depending on the setup used. For example, results in **Error! Reference source not found. Figure 13** show that four lamps in the “Medium” scenario provide inactivation within 2% of the five lamps. This would result in an

approximate **90% reduction in pathogen load being achieved for an effective electrical power consumption of 1.9 W m^{-3} (4 lamps x 15 W / 32.25 m^3).**

As a comparison, to achieve the same additional ventilation rate of 27 ACH using HEPA filter type units, it would be necessary to provide a total Clean Air Delivery rate of 864 m^3/hr. Power consumption for a Philips AC3033 operating at 290 m^3/hr is around 16W; three of these units (total 870 m^3/hr) would be needed to achieve a 90% reduction which would result in an electrical power load of 1.5 W per m^3 of room volume. Therefore, the energy efficiency of Far-UVC is currently comparable to a good quality HEPA device. However, the number of HEPA devices to room volume ratio that would be needed is likely to be impractical in reality due to space and noise implications.

Finally, current Far-UVC lamp technology is currently very inefficient at converting electrical power to Far-UVC, approximately 0.6% (or 0.04% if the Far-UVC is attenuated to remain within UK exposure limits). With new technology (for example LEDs), or an improvement in existing lamp efficiency, the same pathogen inactivation could be achieved for lower electrical power consumption. A typical electrical-to-optical efficiency target is 30%.

7.3 Optical Power Requirements

Each lamp emits approximately **100 mW** of Far-UVC. Fitting a logarithmic curve (y = 11.547ln(x) + 70.827, where y is percent reduction and x is power per unit volume) to the results from this chamber a 90% reduction in *S. aureus* can be achieved by **5.3 mW of Far-UVC per m^3 of room volume** (Sense check: 5.3 mW optical power at 0.04% electrical-to-optical efficiency is 13.3 W electrical power, approximately 15 W). If the computer modelling is accurate and four lamps would be roughly equivalent to five lamps then a 90% reduction in pathogen could be achieved by **4.6 mW of Far-UVC per m^3 of room volume** (% reduction = 11.897ln (power per unit volume) + 71.815)**.**

Room volume may not be the best metric to use when planning deployment. It may be more appropriate to base the deployment on the room area, as long as the peak irradiance is maintained at the UK exposure limit. In such a scenario **11.9 mW of Far-UVC per m^2 of room area (5 lamps, y = 11.547ln(z) + 61.412) or 10.4 mW (4 lamps y = 11.897ln(z) + 62.114),** where z is the power per unit area**.**

7.4 Real-world Hospital Room Examples

Using the analysis from the previous sections, **Table 10** shows calculations of hypothetical number of Far-UVC lamps with diffuser required in real hospital rooms to achieve a minimum of 90% *S. aureus* reduction. In small to medium sized rooms, 1 – 2 lamps with diffuser are required and there is no difference between calculations based on 4 (simulation) or 5 (experimental) lamps. In larger rooms the number of lamps required is less clear and would benefit from computer modelling.

Table 10: Estimated number of Far-UVC lamps required in a number of healthcare scenarios based on data from rooms at Ninewells Hospital, Dundee

	Two-person office (P8 013, Level 8, Photobiology Unit, Ninewells Hospital, Dundee).	**Outpatient consulting room (Consulting 3, Dermatology Dept. Ninewells Hospital Dundee)**	**Seminar Room (Dermatology Dept. Ninewells Hospital, Dundee)**
Length (m)	3.0	4.3	12.3
Width (m)	3.2	3.7	6.2
Area (m2)	9.6	15.9	76.3
Height (m)	2.5	2.5	2.5
Volume (m3)	24	39.8	190.7
(experiment) # of lamps (Power consumption) Area based calculation Volume based calculation (# lamps)	9.6 m^2 x 11.9 mWm^{-2} = 114.2 mW = **2 lamps (30 W)** 24 m^3 x 5.3 mWm^{-3} = 127.2 mW = **2 lamps (30 W)**	189 mW = **2 lamps (30 W)** 211 mW = **3 lamps (45 W)**	908 mW = **10 lamps (150W)** 1011 mW = **11 lamps (165W)**
(simulation) # of lamps (Power consumption) Area based calculation Volume based calculation	9.6 m2 x 10.4 mWm-2 = 99.8 mW = **1 lamp (15 W)** 24 m^3 x 4.6 mWm^{-3} = 110.4 mW = 2 **lamps (30 W)**	165 mW = **2 lamps (30 W)** 183 mW = **2 lamps (30 W)**	794 mW = 8 **lamps (120 W)** 877 mW = 9 **lamps (135 W)**

8 Conclusions

Overall, our study concludes that Far-UVC has substantial potential to reduce the concentration of microorganisms in the air and that it is also likely to bring benefits in reducing contamination of surfaces. It is likely to be an energy efficient and safe way of enhancing airborne infection control which can provide higher equivalent ventilation rates than alternative approaches. Our findings are based primarily on experiments and models from controlled settings which do not fully consider all of the factors present in a real-world setting. However we suggest that Far-UVC is a promising technology which merits further exploration. We have detailed specific conclusions, implications and recommendations for further research below.

8.1 Experimental study

The experimental study shows that Far-UVC effectively reduces the airborne pathogen load in a room under controlled conditions. We have tested devices against two microorganisms, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*, and the results demonstrate both are inactivated suggesting that Far-UVC is very likely to inactivate pathogens that are relevant to healthcare settings. Lab scale studies carried out by other groups internationally suggest that Far-UVC is also effective against a range of viruses.

The results from our preliminary work that demonstrated inactivation at one ventilation rate (Eadie et al. 2022) have been shown in this study to be robust to changes in ventilation regime, ventilation rate and sample location. As expected Far-UVC is more effective when more lamps are used and hence there is a higher quantity of UV in the room. We also see in both experiments and computational modelling that having lamps distributed across the room leads to results that have less variability than having a single UVC lamp in the room. Experimental results show that the difference with ventilation regime and sample location are small, and it is likely that the differences we see are driven by variations in experiments more than the influence of the set-up. As expected the relative performance of the Far-UVC is better at a lower ventilation rate, and we also see less variation in the results.

Initial experiments to explore the ability of a Far-UV device to inactive microorganisms at closer proximity to a source show promise, with a reduced but still substantial reduction in concentration seen at the closer source-sampling distance

set up. However, experiments to measure the influence of distance are challenging to set-up and we were only able to conduct a small number of tests during the timescale for this study.

8.2 Computational modelling and analysis.

Computational models results show excellent agreement with the experimental results suggesting that the model is able to effectively capture the UVC field distribution, airflow paths and inactivation of pathogens. Results suggest that the optimum number of lamps per unit volume could be lower than used in experiments, with modelling suggesting that 4 lamps may have produced results very similar to the 5 lamps used within the chamber study. This would need to be explored with further experiments.

A simple theoretical analysis of inactivation performance at different ventilation rates concurs with both experiments and computational model findings and illustrates the relative benefit of the Far-UVC devices is greatest in poorly ventilated rooms; this is the case for all additional air cleaning technologies.

The overall aim of adding Far-UVC to a room would be to optimise inactivation of pathogen for the lowest possible electrical power input. Our results provide guidance with current lamp wall plug efficiency, which is only about 1%, i.e. a 15 W lamp produces about 0.1 W of Far-UVC. In the chamber scenario used in our study, we calculate that a 90% reduction in microbial concentration could be achieved with around 1.9 W/m^3 of electrical power. To achieve the equivalent benefits with HEPA filter based devices would require a similar power input (around 1.5 W/m^3) but would be challenging due to space and noise constraints.

8.3 Implications and Future Research

8.3.1 Health Effects

We have not measured health effects in this study, however our other ongoing work and international evidence has not identified any acute effects, such as erythema (redness), on human skin with filtered KrCl lamps - even at very large exposures above guideline limits. Typical deployment of the technology in an office environment has also demonstrated no eye discomfort in humans [Kousha et al. In preparation], although (anecdotally) deliberate close proximity direct viewing of these

sources does cause immediate irritation (personal communication). Data on animal eyes has shown limited penetration without permanent damage at exposures within guideline exposure limits. Evidence from cell and animal studies suggests that long term Far-UVC exposure is unlikely to cause non-melanoma skin cancer. Whilst the physics of limited penetration depth from Far-UVC indicates other long-term risks are low, research is needed to rule out the induction of melanoma skin cancer or long-term immune-mediated adverse effects.

8.3.2 Potential Application in Healthcare Settings

We have not directly considered usability and acceptability in this study, but both are important factors for a real-world deployment. Our experience across ongoing studies and through interaction with others in the UK and internationally working on Far-UVC and other air cleaning technologies suggests that the following are important to consider in the next stage of an evaluation:

- Communication/consultation with staff and patients. Far-UVC (as with other open-field UV technologies) when used in occupied rooms results in some exposure to the UV light for people. While any application would have to comply with exposure limits, it is also important that work is carried out to gauge understanding of Far-UVC for those exposure and to evaluate any concerns or views around the potential benefits. Some people may be concerned about “radiation” while others could see the technology as providing a “safe” environment and hence other protocols do not need to be followed. Evidence for both of these aspects is currently very limited.
- Evaluation of product design and robustness. Lamps used in our studies were modified for the experimental scenarios including adding in diffusers to reduce the UVC output and to change the operational setting from an on/off cycle to a constant output; this was essential to be able to measure reliably in an experimental set up. We have not carried out any formal assessment of product quality, but have already seen a small number of lamp failures – it would be important to understand the reliability of these devices from manufacturers. As a relatively new technology it is expected that product quality and reliability will improve as lamp technology develops further. There

are a wide range of different lamps on the market and we have not carried out any assessment of which are most suitable for healthcare application.

- Consideration of which spaces would be most suitable for installation. Although Far-UVC is considerably safer than other wavelengths of UV light, the technology does result in exposure for people. It would therefore be important to consider who would be exposed for how long, and whether there are any groups who could be more vulnerable/concerned by the use of Far-UVC. Exposure limits are based on occupational settings and assume an 8 hour exposure over a 24 hour period. In settings where people could be exposed for longer periods of time, it may be necessary to reduce the Far-UVC irradiance, which may result in a system that is less effective. As there is very limited data on application we would suggest that in the first instance it may not be appropriate to implement Far-UVC in settings where the same person is exposed continuously for 24 hours or more. It is likely that spaces such as toilets, bathrooms, waiting rooms and some treatment rooms may be the most appropriate places to set up trial deployments of Far-UVC. These spaces tend to have intermittent occupancy and may be more appropriate for studies to understand real-world application and acceptability.

8.3.3 Future Research

Our study has shown that Far-UVC has a great deal of potential, however our experiments and computational models are of well-defined and very controlled scenarios without the complexity of fixtures, furnishings or people. Alongside trial deployments highlighted above, there remain a number of research questions which would further inform efficacy and application:

- We have considered three microorganisms in the timescale of this study, two bacteria and a bacteriophage. In a previous study we have some very preliminary data from work with influenza, however it is challenging to work with viruses in chamber studies. It would be important to test against a wider range of microorganisms including fungi.
- Our experiments were all carried out at normal-warm room temperatures and normal humidity. Within the timescale of the study were not able to explore the influence of these parameters, but further research is needed, particularly

as evidence from 254nm UVC work suggests that performance may be lower in higher humidity environments.

- We have focused on the impact of Far-UVC on microorganisms in air, and alongside the air samples we have measured the impact on deposition onto surfaces. However we have not looked at the impact of Far-UVC on surface contamination over time and in environments where contamination can happen due to hand contacts as well as deposition. That Far-UVC is a technology which exposes the whole room to UVC light, means that it has the potential to more widely contribute to surface hygiene. It is not considered as a decontamination technology in this study, however it would be beneficial to understand the routine impacts on surface bioburden.
- Our experiments are carried out using aerosolisation of the microorganisms in distilled water using a colison nebuliser. This is a very common approach for aerosol studies as it is a reliable method that generates a consistent aerosol with a narrow size range. However, this does not fully represent the aerosol size range or composition of human respiratory aerosols. Experiments using realistic human aerosol generation are more complex – we hope to explore this, and the effects of distance from the source further in our future work.
- Some air cleaning technologies have been associated with the generation of chemical byproducts including ozone. 222nm and the lamps used in our study are not known to produce ozone or other byproducts, but we have not measured any impacts of the Far-UVC on indoor air chemistry. International evidence suggests that this risk is very low, however it would be advantageous for further research to evaluate this possibility.

9 References

Beggs, C.B., Noakes, C.J., Sleigh, P.A., Fletcher, L.A., Kerr, K.G. (2006) Methodology for determining the susceptibility of airborne microorganisms to irradiation by an upper-room UVGI system. *Journal of Aerosol Science*, 37(7), 885-902

Cantium Scientific Limited 2015. Bioaerosol Sampler Operating Manual MicroBio MB2. April.

Eadie, E., Hiwar, W., Fletcher, L., Tidswell, E., O'Mahoney, P., Buonanno, M., Welch, D., Adamson, C.S., Brenner, D.J., Noakes, C. and Wood, K. 2022. Far-UVC (222 nm) efficiently inactivates an airborne pathogen in a room-sized chamber. *Scientific Reports*. **12**(1), pp.1–9.

Gilkeson CA, Noakes CJ (2013) Application of CFD Simulation to Predicting Upper-Room UVGI Effectiveness Photochemistry and Photobiology, 89(4):799-810

Hiwar, W., Kharrufa, H., King, M.-F., Salman, N., Fletcher, L. and Noakes, C. 2020. Multiplate air passive sampler to measure deposition rate of airborne microorganisms over time. *In*: *The 16th Conference of the International Society of Indoor Air Quality & Climate*., pp.811–816.

King, M.F., Noakes, C.J., Sleigh, P.A. and Camargo-Valero, M.A. 2013. Bioaerosol deposition in single and two-bed hospital rooms: A numerical and experimental study. *Building and Environment*. **59**, pp.436–447.

Mcdonagh, A., Noakes, C. and Fletcher, L.A. 2013. Experimentally Evaluating the Effectivness of an Upper- Room UVGI System *In*: *11 REHVA World Congress, Clima 2013- Energy efficient, smart and healthy buildins, 16-19 June 2013* .

Noakes, CJ. Fletcher LA., Sleigh PA., Booth WB., Beato-Arribas B., Tomlinson N. 2009. Comparison of Tracer Techniques for Evaluating the Behaviour of Bioaerosols in Hospital Isolation Rooms *In: Healthy Buildings 2009, Syracuse 13-17th September*

Wood, K., Wood, A., Peñaloza, C., Eadie, E., 2021. Turn up the lights, leave them on and shine them all around—numerical simulations point the way to more efficient use of far-uvc lights for the inactivation of airborne coronavirus.

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National Infection Prevention and Control Manual: Methodology

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Version	Date	Summary of changes
1.0	November 2016	New document
2.0	July 2017	Addition of section 3.3.4 – Grading as 'mandatory' Addition of search terms for TBPs literature reviews 'Infection Control During Care of the Deceased' and 'Personal Protective Equipment (PPE) for Infectious Diseases of High Consequence (IDHC).'
3.0	September 2019	Updated to include two-person systematic methodology. Grading of recommendations updated to include new system based on HICPAC grading. New search strategies including this for CINHAL included for select literature reviews - more to be included as work progresses.
4.0	November 2022	Updated to include new ARHAI Scotland NIPCM governance structure. Update of search strategies in Appendix 5.
4.1	January 2024	Update of search strategies for hand hygiene products and skincare in Appendix 5

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Document Information

Purpose:	This document describes the processes undertaken and governance arrangements for development of the National Infection Prevention and Control Manual.
Target audience:	All persons involved in the development of the NIPCM. Available to all NHSScotland staff and the wider public.
Circulation list:	Infection Control Managers, Infection Prevention and Control Teams, Public Health Teams.
Description:	This document describes the methodology for developing the NIPCM, it should be used as a reference for all those involved in the development of the NIPCM.
Review schedule:	Following scheduled review of related SOPs.
Cross reference:	The National Infection Prevention and Control Manual.

Contents

1. Introduction

The NHSScotland National Infection Prevention and Control Manual (NIPCM) was first published on 13 January 2012, by the Chief Nursing Officer (CNO (2012)1) http://www.sehd.scot.nhs.uk/cmo/CNO(2012)01.pdf , and updated on 17 May 2012 (http://www.sehd.scot.nhs.uk/cmo/CNO(2012)01update.pdf).

The NIPCM was endorsed on 3 April 2017 by the Chief Medical Officer (CMO), Chief Pharmaceutical Officer (CPO), Chief Dental Officer (CDO) and Chief Executive Officer of Scottish Care.

The NIPCM is an evidence-based practice guide for use in Scotland containing Standard Infection Control Precautions (SICPs) and Transmission Based Precautions (TBPs), guidance for prevention and management of healthcare infection incidents, outbreaks and data exceedances, and an addendum for IPC within neonatal settings. To support care homes successfully adopt and implement the NIPCM the Infection Prevention and Control Manual for older people and adult care homes (CH IPCM) was added to the NIPCM in May 2021. The NIPCM is intended to reduce the risk of Healthcare Associated Infection (HAI) and ensure the safety of those being cared for, staff and visitors in the care environment.

In 2022, a new chapter for the NIPCM was developed (Chapter 4), which covers infection prevention and control (IPC) in the built environment and decontamination. Chapter 4 will initially exist as a repository for evidence reviews and tools relating to IPC in the built environment including delivery of appropriate decontamination within health and care settings and risk mitigation for water-based pathogens.

The NIPCM aims to:

- make it easy for care staff to apply effective infection prevention and control precautions
- reduce variation and optimise infection prevention and control practices throughout Scotland
- help reduce the risk of HAI
- help align practice, monitoring, quality improvement and scrutiny

It is expected that all NHSScotland employees and all NHSScotland health and care settings apply guidance contained within the NIPCM. It can also be used in other care settings where it should be considered best practice.

A number of supporting tools are available to complement the NIPCM including a compliance monitoring tool which may be utilised locally to monitor and record compliance with elements of the NIPCM. In April 2016 the National Infection Prevention and Control Manual website was launched to present the NIPCM and its associated literature reviews and supporting tools on a single standalone website which is also mobile device friendly.

The NIPCM is underpinned by systematic literature reviews which summarise the available evidence and highlight research gaps.

This document outlines the methodology for producing the NIPCM.

2. Governance Process

2.1 Purpose

It is fundamental to the integrity and applicability of the NIPCM that a wide group of stakeholders are involved in all stages of its development. Involving stakeholders from appropriate multidisciplinary groups during development of the NIPCM ensures that its recommendations are appropriate, practical and acceptable in all health and care settings.

The governance process for the NIPCM is split across three levels.

- **Level 1** provides governance for each of ARHAI Scotland's six Priority Programmes, with an Oversight & Advisory Group overseeing the Priority Programmes, and associated Working Groups reporting into the Oversight & Advisory Group.

  For the NIPCM, there are three relevant Priority Programmes:

  - National Policy, Guidance and Evidence (NPGE) programme
  - Infection Control in the Built Environment & Decontamination (ICBED) programme
  - Community Infection Prevention and Control (CIPC) programme

- **Level 2** provides collective governance for the six Programmes with reporting into the ARHAI Scotland Senior Management Team.
- **Level 3** is ARHAI Scotland reporting into the NHSScotland Assure Divisional Management Team (DMT).

2.2 Membership

2.2.1 Working Groups

The NPGE Working Group has at least one representative (plus a deputy) from each of the following professional organisations:

- Infection Control Managers (ICM) Network
- Infection Control Nurses (ICN) Network
- Infection Control Doctors (ICD) Network
- Scottish Microbiology & Virology Network
- CIPC working group
- ICBED working group
- Scottish Ambulance Service
- Domestic Services Expert Group (DSEG)
- Linen Services Expert Group (LSEG)
- Health Facilities Scotland (HFS) (by invite)
- Occupational Health & Safety, NHS Scotland
- NHS Education for Scotland (NES)
- Scottish Executive Nurse Directors
- Scottish Government Health and Social Care Directorates (observing only)
- Health and Safety

Members for working groups are recruited by an invitation sent to NHS Board or organisational executive leads to nominate representatives and deputies. All members must be employed in a

relevant position i.e. related to healthcare associated infection and infection control, or health protection. A lay representative is also engaged for the lifespan of the Working Group. This person will have an interest in the NHS and/or health care in general and the reduction of the incidence and impact of HAI in Scotland through applicable and accessible infection prevention and control guidance. This person will also have a good understanding of the subject matter and will be a resident of a local NHS Board. The lay representative is expected to attend all meetings and comment on recommendations from the perspective of patients.

The ICBED Working Group has at least one representative (plus a deputy) from each of the following professional organisations:

- Infection Control Managers (ICM) Network
- Infection Control Doctors (ICD)
- Infection Control Nurses (ICN) Network
- NHS Education for Scotland (NES)
- Scottish Ambulance Service (SAS)
- Strategic Facilities Network
- Property and Support Services Division (PSSD)
- Domestic Services Expert Group (DSEG)
- Linen Services Expert Group (LSEG)
- Health Facilities Scotland (HFS)
- Scottish Government Health and Social Care Directorates (observing only)

The CIPC Working Group has at least one representative (plus a deputy) from each of the following professional organisations:

- Infection Control Managers (ICM) Network
- Health Facilities Scotland (HFS)
- Scottish Care
- NHS Education for Scotland (NES)

- Scottish Social Services Council (SSSC)
- Health Improvement Scotland (HIS)
- Care Inspectorate (CI)
- NHS Board Care Home Assurance Lead
- Dental Services Expert Group (DSEG)
- Care Home representative

The CIPC working group currently has a remit to support content additions and updates to the care home manual. The membership will be expanded as the remit of the CIPC programme expands beyond care homes to wider community settings.

2.2.2 IPC Oversight and Advisory group

The IPC Oversight and Advisory group has at least one representative (plus a deputy) from each of the following professional organisations:

- Infection Control Managers Network
- Infection Control Doctors Network
- Scottish Executive of Nursing Director (SEND) (Deputy)
- Health Facilities Scotland
- Scottish Government HAI Policy Unit
- NHS Education for Scotland
- Care Inspectorate
- ARHAI SONAAR
- ARHAI Data and Intelligence
- ARHAI Nurse Consultant Infection Control
- ARHAI Senior Nurse Infection Control
- ARHAI Lead Healthcare Scientist

2.3 Roles and responsibilities

The roles and responsibilities of all Working Group members are laid out in full in the terms of reference (ToR) corresponding to each group. Briefly, Working Group members must:

- Contribute to the consultation process on the NIPCM (including literature reviews and any supporting documents/tools); feeding back the views of the professional groups/ organisations they represent, such as operationalisation of guidance and barriers to implementation.
- Contribute to the identification of evidence/research gaps in the literature pertaining to the NIPCM and support the development of research studies to enhance the evidence base.
- Identify/review/update new/existing tools/procedures/systems that could assist Scottish health and care settings and ARHAI Scotland in the prevention, identification and control of healthcare infection outbreaks and incidents.

IPC Oversight and Advisory group members must:

- Contribute to the continual development of the NIPCM.
- Provide expert opinion/support to the Working Groups on the development of additional guidance.
- Agree the content of any supporting documentation and tools to ensure they are implementable across appropriate sectors for which they are applicable within Scottish health and care settings.
- Contribute to the consultation and testing process of any new supporting documents and tools if required.
- Provide input at meetings, representing the views of all appropriate staff members /groups within their representing/professional body.

2.4 Meetings

Meetings of the Working Groups are bi-monthly and the IPC Oversight and Advisory Group meetings are scheduled on a quarterly basis for the lifespan of the groups. In order for a meeting to be quorate, the following representatives must be present: ARHAI Scotland Nurse

Consultant (programme lead), Chair (or deputy if Chair is absent), a representative from one of the following networks - Scottish Microbiology and Virology Network (SMVN), Infection Control Managers (ICM) Network or Infection Control Doctors (ICD) Network – plus 3 other external (non-ARHAI Scotland) members.

2.5 Competing interests

All members (including chairs) of both the Working Groups and IPC Oversight and Advisory Group are required to declare any competing interests in accordance with the NIPCM competing interests policy (appendix 2).

3. Literature review methodology

The need to undertake a new literature review is determined by stakeholder engagement with Working Groups during which a scoping review is undertaken by ARHAI Scotland to ensure there isn't any existing evidence-based guidance that may be suitable/appropriate for modification for Scotland – in which case, a new literature review may not be required. If there is existing evidence-based guidance, it must achieve an AGREE rating of 'recommend' or 'strongly recommend' (see Section 3.3 for detail).

Two methods for literature reviewing are currently in use for production of the NIPCM: a single-person methodology and a two-person methodology. It is intended that all NIPCM literature reviews will be updated using the two-person methodology by end 2024. A summary comparison of the two methods is provided in Appendix 6: Comparison of single-person and two-person methodology.

3.1 Development of research questions

The question sets within the literature reviews were originally based on the recommendations of the original Model Policies (previously used in NHSScotland (archived December 2011)). Modifications to research questions, including additions, are posed if there is a need to address emerging infection control issues that have been identified by the IPC Oversight and Advisory Group, or common themes emerging from stakeholder enquiries and infection

incidents/outbreaks reported to ARHAI Scotland or identified in the literature. All question sets are drafted by the lead healthcare scientist in collaboration with Senior Infection Control Nurses and agreed by consultation with the relevant Working Groups as well as relevant experts co-opted from within, healthcare, academia or other professional organisations, and signed off by the relevant lead ARHAI Scotland Nurse Consultant Infection Control.

3.2 Identifying evidence

In both the single- and two-person methodologies a lead scientist is responsible for running searches and retrieving articles. First and second stage screening and selection of relevant articles is carried out independently either by a single reviewer or by two reviewers. In a single-person review there is no cross-checking of included and excluded articles, in a two-person review the final list of included articles is agreed jointly: if agreement cannot be reached the final decision will be made by the IPC Lead Healthcare Scientist. All search results, exclusions and consensus decisions are recorded for two-person reviews and, from 2022 onwards, presented in a PRISMA format within the literature review.

3.2.1 Search strategies

Search strategies for literature reviews are initially developed by healthcare scientists using the PICO framework; these undergo a consultation with the relevant Working Groups and the final searches are further optimised by the NSS library service. A complete list of NIPCM search strategies is available in Appendix 5: Literature review search strategies.

3.2.2 Databases and resources searched

The following electronic databases are searched for all relevant papers using the search terms in appendix 5:

- Medline
- Embase
- Cinahl (Cumulative Index to Nursing and Allied Health Literature)

Depending on the literature review topic, additional databases may be accessed by recommendation of the NSS Library service. The following online resources are also searched where appropriate in order to identify any relevant legislation, policy, guidance documents and any grey literature:

- The Cochrane Library
- Scottish Government Health Department (SGHD)
- Department of Health and Social Care (DHSC)
- World Health Organization (WHO)
- US Centers for Disease Control and Prevention (CDC)
- UK Health Security Agency (UKHSA)
- Public Health Wales
- Public Health Agency Northern Ireland
- Public Health Scotland
- European Society of Clinical Microbiology and Infectious Diseases (ESCMID)
- The National Institute for Health and Care Excellence (NICE)
- Scottish Intercollegiate Guidelines Network (SIGN)
- European Centre for Disease Prevention and Control (ECDC)
- Society for Healthcare Epidemiology of America (SHEA)
- Association for Professionals in Infection Control and Epidemiology (APIC)
- National Resource for Infection Control (NRIC)
- UK Scientific Advisory Group for Emergencies (SAGE)
- UK Health and Safety Executive (HSE)

3.2.3 Inclusion/exclusion criteria

Titles and abstracts are reviewed by subject relevance (inclusion), the following exclusion criteria are then applied.

Exclusion:

- item is not applicable to health or social care settings
- item is focussed on compliance/promotion/monitoring or effectiveness of training
- item studies intervention(s) as part of a bundled approach
- item is appraised as having an unacceptable level of bias i.e. SIGN50 level 1- or 2-
- item is not available in English language
- item uses animal models of infection

Additional and/or a modified exclusion criteria may be applied depending on the subject area and will be detailed within the individual literature review.

3.3 Critical appraisal and grading of evidence

Identified studies and guidance documents are appraised and graded using the SIGN50 methodology and AGREE tool, respectively. A lead reviewer critically appraises each study or guidance document. In two-person reviews a second reviewer carries out a check of a minimum 30% of the included studies. Errors or omissions are resolved by discussion, a final decision on any disagreements is made by the IPC Lead Healthcare Scientist.

3.3.1 SIGN 50 levels of evidence

Grade	Description
1++	High quality meta analyses, systematic reviews of RCTs, or RCTs with a very low risk of bias
1+	Well conducted meta analyses, systematic reviews of RCTs, or RCTs with a low risk of bias
1-	Meta analyses, systematic reviews of RCTs, or RCTs with a high risk of bias
2++	High quality systematic reviews of case-control or cohort studies. High quality case-control or cohort studies with a very low risk of confounding, bias, or chance and a high probability that the relationship is causal
2+	Well conducted case control or cohort studies with a low risk of confounding, bias, or chance and a moderate probability that the relationship is causal

Grade	Description
2-	Case control or cohort studies with a high risk of confounding, bias, or chance and a significant risk that the relationship is not causal
3	Non-analytic studies, e.g. case reports, case series
4	Expert opinion

3.3.2 AGREE grades of recommendation

Strongly recommend: This indicates that the guideline has a high overall quality and that it can be considered for use in practice without provisos or alterations.

Recommend: This indicates that the guideline has a moderate overall quality. This could be due to insufficient or lacking information in the guideline for some items. If provisos or alterations are made the guideline could still be considered for use in practice, in particular when no other guidelines on the same topic are available.

Would not recommend: This indicates that the guideline has a low overall quality and serious shortcomings. Therefore, it should not be recommended for use in practice.

4. Development of recommendations

Following assessment of the extant scientific literature, evidence tables are compiled summarising each item and discussing its impact on/contribution to the specified topic area. Evidence tables are used in conjunction with the SIGN50 considered judgment form (appendix 3) to synthesise and grade draft recommendations based on the volume, consistency, applicability etc. of the available evidence. Draft recommendations for practice are made by the lead reviewer and Senior Nurse Infection Control and are based on an assessment of the extant professional and scientific literature. Draft recommendations then undergo an internal consultation with ARHAI Scotland Senior Nurses Infection Control, the IPC Lead Healthcare Scientist and relevant colleagues from Health Facilities Scotland where applicable, and are then approved for external consultation by the Nurse Consultant Infection Control responsible for the review. Following a period of external consultation (see section 3.5) final recommendations are agreed by consensus amongst Working Group members.

4.1 Grading of recommendations

Recommendations are given a grade to highlight the strength of evidence underpinning them, the NIPCM grades of recommendations are as follows*:

Grade	Descriptor	Levels of evidence
Mandatory	'Recommendations' that are directives from government policy, regulations or legislation	N/A
Category A	Based on high to moderate quality evidence	SIGN level 1++, 1+, 2++, 2+, AGREE strongly recommend
Category B	Based on low to moderate quality of evidence which suggest net clinical benefits over harm	SIGN level 2+, 3, 4, AGREE recommend
Category C	Expert opinion, these may be formed by the NIPC groups when there is no robust professional or scientific literature available to inform guidance.	SIGN level 4, or opinion of NIPC group
No recommendation	Insufficient evidence to recommend one way or another	N/A

*Literature reviews published before October 2018 use the SIGN50 (1999-2012) ABCD system for grading recommendations; this will be phased out as reviews are updated, anticipated completion by end 2024.

4.2 External consultation

All literature reviews undergo a process of external consultation to ensure recommendations are unbiased and appropriate for all care settings where applicable. Literature reviews are disseminated via the relevant Working Group (see section 2.1) to each of the professional bodies listed in section 2.2 accompanied by a literature review evaluation tool. The evaluation tool may be modified as appropriate for each review, an example is provided in appendix 4. Each member of the Working group is expected to collate and return the comments of the professional body/organisation they represent using the literature review evaluation tool. Where it is deemed necessary, additional experts/professional groups relevant to the topic area are included in the consultation process. The ARHAI Scotland administration team collates all feedback from the group which is then addressed by the lead reviewer and lead NCIC, and any changes required are made to the final literature review and recommendations. Any points that

require further discussion are brought to the next Working Group meeting to reach consensus, or are shared electronically via a further consultation. Where consultation cannot be reached by the Working Group, a final decision is made by the IPC Oversight & Advisory Group by majority vote.

5. Development of the NIPCM

Following approval of the literature review and recommendations by the Working Group, literature review recommendations are incorporated into the relevant section/chapter of the NIPCM including the care home manual where appropriate. The recommendations are consolidated into high level practice statements to allow a streamlined presentation which is easier for staff nearest to those receiving care to read, understand and put into practice. The NIPCM is not intended to state recommendations for specific sectors or specialities. The individual recommendations and evidence (including grade(s)) underpinning these is presented in the associated literature reviews.

The SICPs literature review recommendations are consolidated under the '10 elements of SICPs' in Chapter 1:

- Patient placement
- Hand hygiene
- Respiratory and cough hygiene
- Personal protective equipment
- Safe management of care equipment
- Safe management of the care environment
- Safe management of linen
- Safe management of blood and body fluid spills
- Safe disposal of waste
- Occupational safety: prevention and exposure management (including sharps)

The TBPs literature review recommendations are consolidated under the following headings in Chapter 2:

- Patient placement
- Safe management of patient care equipment in an isolation room/cohort area
- Safe management of the care environment
- Personal protective equipment
- Infection prevention and control during care of the deceased

Chapter 3 is underpinned by two literature reviews which inform the sections:

- Definitions of Healthcare Infection Incident, Outbreak and Data Exceedance
- Detection and recognition of a Healthcare Infection incident/outbreak or data exceedance

New chapters, and any changes to the NIPCM out-with the literature review process, are agreed by a process of consultation with the Working Groups and IPC Oversight & Advisory Group, respectively (see sections 2 and 3.5).

6. Development of supporting tools

To support the implementation of the NIPCM by stakeholders a number of supporting tools are available. The tools are included in the NIPCM as appendices and are typically in the form of diagrams to illustrate processes and procedures, or algorithms to aid decision making processes. Supporting tools are developed based on stakeholder need and are directly informed by the content of the NIPCM and its associated literature reviews; they are subject to the same consultation process as the literature reviews that underpin them, which ensures they are evidence-based and fit for purpose.

7. Maintaining and updating the NIPCM

The NIPCM is a ‘live’ document; the evidence base underpinning it is under continual review through ‘living’ systematic literature reviews. The evidence base which underpins the NIPCM

recommendations is monitored using monthly autoalerts of Medline and Embase which utilise the search strategies detailed in appendix 5; and RSS feeds for the following organisations:

- ECDC – Epidemiological update
- CDC (Emerging Infectious Diseases Journal, Morbidity & Mortality Weekly Report)
- UK Health & Safety Executive (HSE)
- WHO (News; Disease Outbreak news)
- NICE
- Scottish Government
- UK Government
- Care Quality Commission
- UK Health Security Agency (UKHSA)
- Care Inspectorate

The responsible scientists review all titles and abstracts to identify any evidence that supports, modifies or refutes the recommendations of the NIPCM. Any evidence identified which disagrees with current recommendations is subjected to immediate appraisal and, where appropriate, inclusion in the relevant literature review following the methodology described in section 3 of this document; changes are made to the NIPCM after consulting with the NCIC, relevant Working Group (and if applicable, the IPC Oversight & Advisory Group). Any evidence identified which supports the current recommendations of the NIPCM is collated in an ongoing evidence table which is presented to the IPC Oversight & Advisory Group on a quarterly basis. The identified evidence is subject to full appraisal as per the research methodology and addition to the relevant literature review(s) during the next scheduled update (every 3 years).

Detailed roles and responsibilities for updating the NIPCM can be found in appendix 1.

8. Presentation of guidance

All literature reviews are presented in a standardised format, the contents are limited to:

1. Objectives
2. Methodology

3. Discussion

    3.1 Implications for practice
    3.2 Implications for research

4. Recommendations

5. References

6. Appendices

All draft versions of guidance and supporting tools are finalised by an information officer to ensure version control, consistency of presentation, and accessibility.

8.1 Document control

Document control sheets are standardised, present and up to date on all literature reviews and the NIPCM itself. Document control sheets include:

- current version number
- publication date of current and previous versions
- any changes made to the document if a previous version exists (update level)
- purpose and description of the document
- approvals
- target audience
- a cross-reference section linking to this document and any related literature reviews or guidance documents
- date of next scheduled review

Similarly, all supporting tools should state the publication date, current version number and have ARHAI Scotland/NSS branding.

8.2 Language, clarity and ease of understanding

The NIPCM and all literature reviews produced after September 2018 are formatted in an accessible template to comply with the UK Public Sector Bodies (Websites and Mobile Applications) (No. 2) Accessibility Regulations 2018.

The NIPCM includes a glossary of terms. When a literature review is updated the responsible scientist and Senior Nurse Infection Control/Nurse Consultant in Infection Control determine whether any new terminology has been used that would require addition to the glossary. New terms may also be added at the request of stakeholders e.g. via the IPC Oversight & Advisory Group or associated Working Groups. Abbreviations are avoided where possible, only those that are commonly and frequently used in most care settings e.g. ABHR (alcohol based hand rub) are included.

An Equality Impact Assessment is conducted annually for the NIPCM. Equality analysis is a way of considering the effect on different groups protected from discrimination by the Equality Act, such as people of different ages. This is to ensure the NIPCM will be fully effective for all target groups and to ensure there are no unintended consequences for any groups.

9. Editorial independence

The NIPCM and its associated literature reviews and tools are funded by the Scottish Government. The Scottish Government HAI policy unit is present at meetings of the IPC Oversight & Advisory Group, and the Working Groups; however, this forms part of the governance structure and the representative acts as an observer only i.e. they do not take part in consultations or the forming of recommendations. The representative also complies with the competing interest policy for completeness.

10. Publication and dissemination

The NIPCM and its associated literature reviews and supporting tools are available electronically from the NIPCM website. Any changes or updates to the content of the NIPCM, its associated literature reviews or supporting tools are communicated to stakeholders via a

monthly ARHAI Scotland newsletter; this forms part of an overarching NIPCM communications strategy.

11. Implementation

It is the responsibility of organisations to ensure adoption and implementation of the NIPCM in accordance with local governance policies (see appendix 1). As described in section 6, a number of supporting tools are available to support implementation of the NIPCM. In addition a compliance and quality improvement data collection tool accompanies the NIPCM. This data collection tool has been designed to support SICPs implementation at a local level, e.g. ward level. It can be used by all staff disciplines in any care environment. The tool enables staff to assess compliance with any and all of the 10 SICPs elements as well as TBPs for patient placement and to identify any critical elements that need to be improved and the system changes that can help clinical teams ensure compliance and reduce the HAI risks in their care setting.

ARHAI Scotland collaborates with NHS Education for Scotland (NES) to develop IPC education and training resources for health and social care staff across Scotland. This includes the TURAS Learn IPC Zone and within that the Scottish Infection Prevention and Control Education Pathway (SIPCEP). There is also a TURAS Learn Healthcare Built Environment Zone currently under development.

12. Feedback and enquiries

The NIPCM website has a contact us section to allow frontline staff to comment on the usability of the website and its tools as well as issues with content or clarity. In addition, the ARHAI Scotland IPCT has an enquiry system in place to field queries regarding infection control practices including implementation of the NIPCM. Issues with clarity, presentation, research gaps or barriers to implementation can also be highlighted through this system.

Appendix 1: Roles and responsibilities

The following responsibilities form part of the standard operating procedure (SOP) for maintaining the National Infection Prevention and Control Manual.

A list of roles and responsibilities for adopting and implementing the NIPCM can be found on the NIPCM website.

Nurse Consultant (NC) Infection Control responsibilities

Typically, each Nurse Consultant (NC) as clinical lead for the 3 IPC programmes of work develop and inform content for inclusion within the NIPCM relevant to their respective programmes of work.

- ICBED NC Clinical lead: Chapter 4 and associated tools/appendices;
- CIPC NC Clinical lead: Care Home Manual and associated tools/appendices;
- NPGE NC Clinical lead: All other aspects of the NIPCM not described above.

Governance responsibilities are distributed as follows:

NPGE NC Clinical lead

- Overall lead for the ongoing development and maintenance of the NIPCM as a whole.
- Ensuring oversight and alignment of the various chapters and content within the NIPCM via final sign-off of published content.

NPGE, ICBED and CIPC leads

- Engagement with working groups to ensure content of NIPCM relevant to respective programmes meets the needs of stakeholders.
- Supporting literature reviews to be undertaken by the ARHAI Infection Prevention and Control Team relevant to respective programmes of work.
- Attending and contributing to the IPC Oversight & Advisory Group and Working Groups.
- Proposing changes to and appraising feedback from the NIPCM from the IPC Oversight & Advisory Group and other relevant persons.
- Managing the updates to the NIPCM relevant to respective programmes of work.

- Leading on development of tools relevant to respective programme of work and associated literature reviews.
- Leading on education, communications and promotion of NIPCM content relevant to their respective programmes of work.

Senior Nurse Infection Control responsible for:

- Attending and contributing to the Working Groups.
- Providing clinical input to all stages of the literature review process to support the Healthcare Scientists.
- Preparing updates to the NIPCM based on the information provided by the Healthcare Scientist and feedback from the Working Groups.

Healthcare Scientists responsible for:

- Establishing autoalerts as required i.e. on identification of new subject areas/ agreement with Nurse Consultant Infection Control
- Monitoring outputs of the autoalerts (monthly)
- Screening the titles and abstracts for relevance
- Obtaining potentially relevant papers
- Critically appraising identified literature
- Producing ~~a~~ quarterly summary evidence tables for discussion at the IPC Oversight & Advisory Group
- Updating literature reviews every 3 years or when new evidence will make a major change to recommendations

Information Officer responsible for:

- Making changes to the NIPCM as instructed by the NPGE Nurse Consultant Infection Control
- Editing and formatting of the NIPCM and literature reviews
- Updating the NIPCM website with the NIPCM and literature reviews

Team Administrator responsible for:

- Scheduling meetings, preparing minutes and agenda and other correspondence for the relevant groups.
- Collating comments received from consultation documents sent out for the NIPCM.

ARHAI Scotland Infection Control Team

- Informing Healthcare Scientist(s) of any new literature/guidance/legislation they become aware of which may impact on the NIPCM.

Appendix 2: Competing interests policy and declaration of interests form

Why do we need a competing interests policy?

A competing interests policy strengthens the integrity of the development process for the National Infection Prevention and Control Manual (NIPCM) to ensure the recommendations produced are unbiased, evidence-based and not subject to any outside influence or commercial interests.

Who does this policy apply to?

This policy applies to all persons involved in the development of the NIPCM, its associated literature reviews and supporting tools. All members (including chairs) of the IPC Oversight and Advisory Group and Working Groups and any invited peer reviewers from out with these groups should complete the accompanying declaration of interests form.

How will declared competing interests be managed?

Individuals with competing interests are not eligible to chair the IPC Oversight and Advisory Group and Working Groups. Declared competing interests will be considered by the chair in the first instance, if the potential impact of the declared interest is unclear this will be discussed by the other members of the consensus/steering group(s) and taken to a vote. If declared interests are likely to impact on a significant number of topics the member may be asked to withdraw completely from the consensus/steering group(s). Members who have declared a topic-specific competing interest should withdraw from commenting or contributing to the development of any guidance to which the competing interest applies, an appointed deputy should take their place.

How will this policy be applied?

As per the terms of reference for all groups, members will be asked to declare any new competing interests before each group meeting commences. Out with meetings, new declarations should be made to the relevant chair using the ‘declaration of competing interests’ form, this should be copied to the ARHAI Scotland infection control mailbox for recording. Electronic copies of declaration of interest forms and related correspondence will be archived by ARHAI Scotland. All declarations of interest are solely for the use of the NIPC programme and will be treated as confidential.

What are competing interests?

A competing interest is any interest that conflicts with your official duties, impairs your ability to carry out your duties, and/or impacts on your work. Specifically, this policy describes any interest that may consciously or unconsciously influence your ability to provide independent, unbiased contributions to the development of the NIPCM, or its associated literature reviews and supporting tools.

Competing interests can be financial or non-financial, professional, or personal. Competing interests can arise in relation to an organisation or another person. Examples of conflicts of interest may include:

- A role or association with any commercial healthcare organisation/supplier including:
    - Share holding;
    - A prospect of future employment;
    - Partnerships and other forms of business e.g. consultancy;
- Receiving products directly from a commercial organisation without charge or at a reduced rate for any purpose (does not include unsolicited trial products, small promotional materials such as pens or any product purchased at a reduced rate negotiated by NHS Procurement and Commissioning Facilities);
- Where a family member or close personal relationship exists with an external body or somewhere where you may be in a position to award services to;
- *Membership of professional bodies (voluntary or remunerated) or mutual support organisations, including lobbying or advocacy organisations, political parties, funding bodies such as nongovernmental organisations, research institutions, or charities;
- A position of authority in an organisation in the field of health care;
- Patent applications (pending or actual), including individual applications or those belonging to the organisation to which the member is affiliated and from which the member may benefit;
- Research grants (from any source, restricted or unrestricted);

- Writing or consulting for an educational company;
- An author or associated personally or professionally with an author on any published study or guideline that is being discussed as part of development of the NIPCM or its associated literature reviews and supporting tools.

*Members are expected to present the opinions and concerns of the professional body or organisation they are representing; this is a fundamental process for both the consensus and steering group and includes raising organisational barriers to implementation that have been identified by their peers and colleagues, as such these do not constitute a competing interest.

NIPCM Working Groups and IPC Oversight & Advisory Group

Declaration of Competing Interests

All relevant persons as identified in the NIPCM Working Groups and IPC Oversight & Advisory Group Competing Interests Policy are required to complete and return this form in the event that a competing interest arises that may prevent them from contributing to the development of the National Infection Prevention and Control Manual (NIPCM), its associated literature reviews and supporting tools.

Individual to complete

Name: ……

Job title: ……

Representing body/professional body: ……

……

Email: ……..

Statement of competing interest(s):

(Please provide details of the nature of any competing interests, including whether they apply to the development of the NIPCM in its entirety or to specific sections and whether they are temporary or permanent)

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I confirm that I have read and understood the NIPC competing interests policy and that the information within this form is accurate and complete to the best of my knowledge.

Signed: …….. Date: ……

Signed by Chair: ……. Date: ……

Appendix 3: Considered judgement form (SIGN50)

Question:	Evidence Table Ref:
1. Volume of Evidence - Quantity of evidence on this topic and quality of method	
2. **Applicability** – in Scotland	
3. Generalisability - How reasonable it is to generalise from the available evidence	
4. Consistency - Degree of consistency demonstrated by the available evidence	
5. Potential Impact of the intervention	
6. Other factors to consider while assessing the evidence base	

7. Evidence Statement – synthesis of the evidence relating to this question	**Evidence level**
8. Recommendation -	**Grade of Recommendation**

Appendix 4: Literature review evaluation tool

Once completed, please return to ARHAI Scotland Infection Control Team at:
NSS.ARHAIinfectioncontrol@nhs.scot

Name:	
Organisation and/or network represented:	
Date:	
Literature Review Title:	

*Please provide further detail in comments column.

Does the literature review meet its objectives?		
Yes/No*	**Section/Page No./Line No.**	**Comments/Suggested Amendments**

Are the recommendations linked to the supporting evidence?		
Yes/No*	**Section/Page No./Line No.**	**Comments/Suggested Amendments**

Are the recommendations clear?		
Yes/No*	**Section/Page No./Line No.**	**Comments/Suggested Amendments**

Are there any relevant legislative/mandatory requirements or evidence that have not been included in the literature review?		
***Yes/No**	**Section/Page No./Line No.**	**Comments/Suggested Amendments**

Are there any gaps in this literature review?		
***Yes/No**	**Section/Page No. /Line No.**	**Comments/Suggested Amendments**

Are there any errors in this literature review?		
***Yes/No**	**Section/Page No. /Line No.**	**Comments/Suggested Amendments**

Any further comments? **Please use the box below to write any additional comments):**

Appendix 5: Literature review search strategies

Hand Hygiene (SICPs):

Hand Hygiene Products

Embase & Medline search 2019 - current

1. exp hand disinfection
2. exp Hand Hygiene/
3. hand saniti*.mp.
4. hand rub*.mp.
5. (hand* adj2 wash*).mp
6. (hand* adj2 clean*).mp
7. (Hand adj2 hygien*).mp.
8. 1 or 2 or 3 or 4 or 5 or 6 or 7
9. exp Infections/
10. exp DiseaseTransmission, Infectious/
11. Infection Control/ or exp sterilization/
12. Bacterial Infections/
13. (eat* or ingest* or drink* or consum* or swallow* or inhal* or toxic* or poison*).ti,ab.
14. Refill*.mp.
15. Container*.mp.
16. Dispens*.mp.
17. exp disinfectants/
18. exp soaps/ or exp emulsifying agents/
19. Soap*.mp.
20. exp Anti-Infective Agents, Local/
21. alcohol based hand?rub*.mp.
22. alcohol based hand rub*.mp.
23. ABHR.mp.
24. contaminat*.mp.
25. 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16
26. 17 or 18 or 19 or 20 or 21 or 22 or 23 or 24
27. 8 and 25 and 26
28. limit 27 to (english language and yr="2019 -Current")

CINAHL search 2019-current

S29 S7 AND S27 AND S28

S28 S18 OR S19 OR S20 OR S21 OR S22 OR S23 OR S24 OR S25 OR S26

S27 S8 OR S9 OR S10 OR S11 OR S12 OR S13 OR S14 OR S15 OR S16 OR S17

S26 contaminat*

S25 ABHR

S24 alcohol based hand rub*

S23 alcohol based handrub*

S22 (MH "Antiinfective Agents, Local+")

S21 soap*

S20 emulsifying

S19 (MH "Soaps")

S18 (MH "Disinfectants")

S17 dispens*

S16 container*

S15 refill*

S14 AB eat* or ingest* or drink* or consum* or swallow* or inhal* or toxic* or poison*

S13 TI eat* or ingest* or drink* or consum* or swallow* or inhal* or toxic* or poison*

S12 (MH "Bacterial Infections")

S11 (MH "Sterilization and Disinfection+")

S10 (MH "Infection Control+")

S9 (MH "Communicable Diseases+")

S8 (MH "Infection+")

S7 S1 OR S2 OR S3 OR S4 OR S5 OR S6

S6 hand N2 hygien*

S5 hand N2 clean*

S4 hand N2 wash*

S3 hand rub*

S2 hand saniti*

S1 (MH "Handwashing+")

Hand Washing, Hand Rubbing and Indications for Hand Hygiene

Embase

1. exp Hand Disinfection/
2. exp Hand Washing/
3. ((hand* adj2 hygiene) or (hand* adj2 hygienic*) or hand?wash* or (hand* adj2 wash*) or (hand* adj2 clean*) or (hand* adj2 sanit*) or (hand* adj2 rub*) or (hand adj2 wip*) or (hygiene adj4 facilit*)).ti,ab,kf.
4. exp health care facility/
5. ("health?care facilit*" or hospital* or clinic* or "residential care" or "nursing home*" or "care home*" or "nursing residenc*" or "nursing care facilit*" or "nursing care residenc*" or "nursing residenc*" or "skilled nursing facilit*" or "skilled nursing residenc*" or "long?term care facilit*" or "long?term care residen*" or "convalescent home*" or "convalescent facilit*" or "convalescent residenc*").ti,ab,kf.
6. exp temperature/
7. (water adj2 temperature).ti,ab,kf.
8. (method* or technique* or procedure* or dry* or drie* or nail*).ti,ab,kf.
9. exp jewelry/
10. (jewellery or jewelry).ti,ab,kf.
11. ((wash* adj4 basin*) or (wash* adj4 sink*) or (hand* adj4 basin) or (hand adj4 sink*)).ti,ab,kf.
12. (tap* or faucet*).ti,ab,kf.
13. 1 or 2 or 3
14. 4 or 5
15. 6 or 7 or 8 or 9 or 10 or 11 or 12
16. 13 and 14 and 15
17. limit 16 to (english language and yr="2019 -Current")

Medline

1. exp Hand Hygiene/
2. ((hand* adj2 hygiene) or (hand* adj2 hygienic*) or hand?wash* or (hand* adj2 wash*) or (hand* adj2 clean*) or (hand* adj2 sanit*) or (hand* adj2 rub*) or (hand adj2 wip*) or (hygiene adj4 facilit*)).ti,ab,kf.
3. exp health care facilities/

4. ("health?care facilit*" or hospital* or clinic* or "residential care*" or "nursing home*" or "care home*" or "nursing residenc*" or "nursing care facilit*" or "nursing care residenc*" or "nursing residenc*" or "skilled nursing facilit*" or "skilled nursing residenc*" or "long?term care facilit*" or "long?term care residen*" or "convalescent home*" or "convalescent facilit*" or "convalescent residenc*").ti,ab,kf.
5. exp temperature/
6. (water adj2 temperature).ti,ab,kf.
7. (method* or technique* or procedure* or dry* or drie* or nail*).ti,ab,kf.
8. exp jewelry/
9. (jewellery or jewelry).ti,ab,kf.
10. ((wash* adj4 basin*) or (wash* adj4 sink*) or (hand* adj4 basin) or (hand adj4 sink*)).ti,ab,kf.
11. (tap* or faucet*).ti,ab,kf.
12. 1 or 2
13. 3 or 4
14. 5 or 6 or 7 or 8 or 9 or 10 or 11
15. 12 and 13
16. 14 and 15
17. limit 16 to (english language and dt="20190601-20220628")

CINAHL

S14. S7 AND S13 Published Date: 20190601-20220631; English Language
S13. S8 OR S9 OR S10 OR S11 OR S12
S12. TI (tap* or faucet*) OR (AB (tap* or faucet*)) OR (DE (tap* or faucet*))
S11. TI ((wash* N3 basin*) or (wash* N3 sink*) or (hand* N3 basin) or (hand N3 sink*)) OR (AB ((wash* N3 basin*) or (wash* N3 sink*) or (hand* N3 basin) or (hand N3 sink*))) OR (DE ((wash* N3 basin*) or (wash* N3 sink*) or (hand* N3 basin) or (hand N3 sink*)))
S10. TI (jewellery or jewelry) OR AB ((jewellery or jewelry)) OR DE ((jewellery or jewelry))
S9. TI (method* or technique* or procedure* or dry* or drie* or nail*) OR (AB (method* or technique* or procedure* or dry* or drie* or nail*)) OR (DE (method* or technique* or procedure* or dry* or drie* or nail*))
S8. TI (water N3 temperature) OR AB (water N3 temperature) OR DE (water N3 temperature)
S7. S3 AND S6

S6. S4 OR S5

S5. (MH "Health Facilities+")

S4. TI ("health#care facilit*" or hospital* or clinic* or "residential care" or "nursing home*" or "care home*" or "nursing residenc*" or "nursing care facilit*" or "nursing care residenc*" or "nursing residenc*" or "skilled nursing facilit*" or "skilled nursing residenc*" or "long#term care facilit*" or "long#term care residen*" or "convalescent home*" or "convalescent facilit*" or "convalescent residenc*") OR AB ("health#care facilit*" or hospital* or clinic* or "residential care" or "nursing home*" or "care home*" or "nursing residenc*" or "nursing care facilit*" or "nursing care residenc*" or "nursing residenc*" or "skilled nursing facilit*" or "skilled nursing residenc*" or "long#term care facilit*" or "long#term care residen*" or "convalescent home*" or "convalescent facilit*" or "convalescent residenc*") OR DE ("health#care facilit*" or hospital* or clinic* or "residential care" or "nursing home*" or "care home*" or "nursing residenc*" or "nursing care facilit*" or "nursing care residenc*" or "nursing residenc*" or "skilled nursing facilit*" or "skilled nursing residenc*" or "long#term care facilit*" or "long#term care residen*" or "convalescent home*" or "convalescent facilit*" or "convalescent residenc*")

S3. S1 OR S2

S2. TI ((hand* N1 hygiene) or (hand* N1 hygienic*) or hand#wash* or (hand* N1 wash*) or (hand* N1 clean*) or (hand* N1 sanit*) or (hand* N1 rub*) or (hand N1 wip*) or (hygiene N3 facilit*) or (hand N1 sterili?ation) or (hand N1 sterilize*) or (hand N1 sterilise*)) OR AB ((hand* N1 hygiene) or (hand* N1 hygienic*) or hand#wash* or (hand* N1 wash*) or (hand* N1 clean*) or (hand* N1 sanit*) or (hand* N1 rub*) or (hand N1 wip*) or (hand N1 disinfect*) or (hygiene N3 facilit*)) OR DE (((hand* N1 hygiene) or (hand* N1 hygienic*) or hand#wash* or (hand* N1 wash*) or (hand* N1 clean*) or (hand* N1 sanit*) or (hand* N1 rub*) or (hand N1 wip*) or (hygiene N3 facilit*) or (hand N1 sterili?ation) or (hand N1 sterilize*) or (hand N1 sterilise*))

S1. (MH "Handwashing+")

Skin Care

EMBASE and MEDLINE search 2019 to current

1. exp Hand Disinfection
2. exp Hand Hygiene
3. handwash$.mp.

4. (hand$ adj2 wash$).mp.
5. hand disinfect$.mp.
6. hand hygiene.mp.
7. hand clean$.mp.
8. hand saniti$.mp.
9. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8
10. exp Dermatitis, Contact
11. exp Dermatitis, Atopic/
12. dermatit$.ti,ab,kw.
13. exp Eczema/
14. eczema.ti,ab,kw.
15. Hand Dermatoses
16. exp Skin/
17. exp Skin Care/
18. 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17
19. soap$.mp. 8424
20. Anti-Infective Agents, Local/
21. alcohol based hand rub$.mp.
22. alcohol based hand?rub$.mp.
23. ABHR.mp.
24. exp Emollients/
25. emollient$.mp.
26. exp Dermatological Agent/
27. skin protect$.mp.
28. 19 or 20 or 21 or 22 or 23 or 24 or 25 or 26 or 27
29. 9 and 18 and 28
30. exp "Surveys and Questionnaires"/

31. (health adj2 surveillance).ti,ab.

32. screen$.ti,ab,kw.

33. questionnaire$.ti,ab,kw.

34. exp Skin Tests/ or (skin adj2 examination$).mp. or (skin adj2 surveillance).mp.

35. surveillance.ti,ab,kw.

36. Biological Monitoring/ or monitor$.ti,ab,kw.

37. 30 or 31 or 32 or 33 or 34 or 35 or 36

38. 9 and 18 and 37

39. 29 or 38

40. limit 39 to english language

CINAHL search 2019- current

S34 S24 OR S33

S33 S8 AND S15 AND S32

S25 OR S26 OR S27 OR S28 OR S29 OR S30 OR

S32 S31

S31 monitor*

S30 skin examination*

S29 (MH "Skin Tests+")

S28 (MH "Questionnaires+")

S27 screen*

S26 health N2 surveillance

S25 (MH "Surveys+")

S24 S8 AND S15 AND S23

S23 S16 OR S17 OR S18 OR S19 OR S20 OR S21 OR S22

S22 skin protect*

S21 (MH "Dermatologic Agents+")

S20 emollient*

S19 ABHR

S18 alcohol based hand rub

S17 (MH "Antiinfective Agents, Local+")

S16 soap*

S15 S9 OR S10 OR S11 OR S12 OR S13 OR S14

S14 (MH "Skin Care+")

S13 (MH "Skin+")

S12 eczema

S11 hand dermat*

S10 (dermat*) N2 (irritant*)

S9 (MH "Dermatitis+") OR (MH "Dermatitis, Contact+")

S8 S1 OR S2 OR S3 OR S4 OR S5 OR S6 OR S7

S7 hand* N2 wash*

S6 hand disinfect*

S5 hand saniti*

S4 hand clean*

S3 hand wash*

S2 hand hygiene

S1 (MH "Handwashing+")

Surgical Hand Antisepsis in the Clinical Setting

EMBASE and MEDLINE search 2000 to current

1. exp Hand Disinfection/
2. exp Hand Hygiene/
3. handwash$.mp.
4. (hand$ adj2 wash$).mp.

5. hand disinfection.mp.
6. hand hygiene.mp.
7. hand cleansing.mp.
8. hand saniti$.mp.
9. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8
10. exp Specialties, Surgical/
11. invasive procedure$.mp.
12. exp Operating Rooms/
13. operating theatre$.mp.
14. 10 or 11 or 12 or 13
15. surgical scrub$.mp.
16. (surg$ adj2 scrub$).mp.
17. jewelry.mp.
18. jewellery.mp.
19. technique$.mp.
20. method$.mp.
21. procedure$.mp.
22. dry$.mp.
23. (hygiene adj4 facilit$).mp.
24. exp Health Facility Environment/
25. 15 or 16 or 17 or 18 or 19 or 20 or 21 or 22 or 23 or 24
26. 9 and 14 and 25

Limit 26 to English language

CINAHL 2000 to current

S29 S26 OR S27 (English language)
S28 S26 OR S27
S27 MH "Surgical Scrubbing"
S26 S8 AND S14 AND S24
S25 S8 AND S14 AND S24 149
S24 S15 OR S16 OR S17 OR S18 OR S19 OR S20 OR S21 OR S22 OR S23
S23 MH "Health Facility Environment"
S22 (hygiene) N4 (facilit*)

S21 "dry*"
S20 "procedure*"
S19 "method*"
S18 "technique*"
S17 "jewellery"
S16 "jewelry"
S15 MH "Jewelry"
S14 S9 OR S10 OR S11 OR S12 OR S13
S13 "operating theatre*"
S12 MH "Operating Room Personnel+"
S11 MH "Operating Rooms"
S10 MH "Invasive Procedures+"
S9 MH "Specialties, Surgical+"
S8 S1 OR S2 OR S3 OR S4 OR S5 OR S6 OR S7
S7 "hand disinfection"
S6 "hand saniti*"
S5 "hand cleansing"
S4 (hand*) N2 (wash*)
S3 "handwash*"
S2 "hand hygiene"
S1 MH "Handwashing+"

Management of equipment and the environment

Management of Patient Care Equipment (SICPs and TBPs)

EMBASE and MEDLINE search 2000 to current

1. diagnostic equipment/
2. disposable equipment/
3. (reus* adj3 equipment).mp.
4. (communal adj3 equipment).mp.
5. (non invasive adj3 equipment).mp.
6. medical device/
7. 1 or 2 or 3 or 4 or 5 or 6

8. disinfection/
9. decontamination/
10. decontaminat*.mp.
11. hospital service/
12. disinfectant agent/
13. surfactant/
14. cleaning/
15. infection control/
16. 8 or 9 or 10 or 11 or 12 or 13 or 14 or 15
17. 7 and 16
18. disposable equipment/
19. (dispos* adj3 equipment).mp.
20. (single-use adj3 equipment).mp.
21. 18 or 19 or 20
22. (terminal adj3 clean*).mp.
23. (terminal adj3 disinfect*).mp.
24. deep clean*.mp.
25. (discharge adj3 clean*).mp.
26. 22 or 23 or 24 or 25
27. 21 and 26
28. 17 or 27

Limit 28 to English language

Safe Management of the Care Environment (SICPs)

EMBASE and MEDLINE search 2000 to current

1. disease transmission/
2. infection/
3. exp disinfection/
4. hospital service/
5. communicable disease control/
6. cross infection/
7. infection control/
8. 1 or 2 or 3 or 4 or 5 or 6 or 7

9. cleaning/
10. (environment* adj3 clean*).mp.
11. (environment adj3 contamin*).mp.
12. (environment adj3 disinfect*).mp.
13. (environment* adj3 decontaminat*).mp.
14. (surface* adj3 clean*).mp.
15. (surface* adj3 contaminat*).mp.
16. (surface* adj3 disinfect*).mp.
17. (surface* adj3 decontaminat*).mp.
18. 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17
19. 8 and 18

Limit 19 to English language and human

Safe Management of the Care Environment (TBPs)

EMBASE and MEDLINE search 2000 to current

1. exp disinfection/
2. decontamination/
3. detergent/
4. disinfectant agent/
5. exp contamination/
6. contaminat*.mp.
7. 1 or 2 or 3 or 4 or 5 or 6
8. patient isolation/ or isolation/
9. isolation hospital/
10. cohorting.mp.
11. side room.mp.
12. single room.mp.
13. (patient* adj3 room*).mp.
14. 8 or 9 or 10 or 11 or 12 or 13
15. 7 and 14

Limit 15 to English language

Safe Management of the Care Environment – Isolation and Cohorting (TBPs)

EMBASE and MEDLINE search 2000 to current

1. exp Patient Isolation/
2. exp Hospitals, Isolation/
3. cohorting.mp.
4. exp Patients' Rooms/
5. side room.mp.
6. single room.mp.
7. 1 or 2 or 3 or 4 or 5 or 6
8. decontamina*.mp.
9. exp Disinfection/
10. exp Disinfectants/
11. exp Detergents/
12. exp Decontamination/
13. 8 or 9 or 10 or 11 or 12
14. 7 and 13

Limit 14 to English language

Safe Management of the Care Environment - Terminal Cleaning (TBPs)

EMBASE and MEDLINE search 2000 to current

1. (terminal adj3 clean*).mp.
2. (terminal adj3 disinfect*).mp.
3. deep clean*.mp.
4. (discharge adj3 clean*).mp.
5. 1 or 2 or 3 or 4

Limit 5 to English language

Personal Protective Equipment (PPE)

Aprons and Gowns (SICPs and TBPs)

EMBASE and MEDLINE search from 2000 - Current

1. Gown*.mp
2. Apron*.mp
3. 1 or 2
4. Exp Hospitals/
5. Exp Infections/
6. Exp Infection Control/
7. Exp Disease Transmission, Infectious/
8. 4 or 5 or 6 or 7
9. 3 and 8

CINAHL search from 2000 - Current

1. Gown*
2. Apron*
3. 1 or 2
4. (MH "Hospitals+")
5. (MH "Infection+")
6. (MH "Infection Control+")
7. (MH "Disease Transmission+")
8. 4 or 5 or 6 or 7
9. 3 and 8

Eye/Face Protection (SICPs and TBPs)

EMBASE and MEDLINE search 2000 to current

1. Eye Protective Devices/
2. Goggles.mp
3. Face shield*.mp
4. Visor*.mp
5. Safety glasses.mp

6. 1 or 2 or 3 or 4 or 5
7. Exp Hospitals/
8. Exp Infections/
9. Exp Infection Control/
10. Exp Disease Transmission, Infectious/
11. 7 or 8 or 9 or 10
12. 6 and 11

CINAHL search from 2000 to current

1. Eye Protective Devices
2. goggles
3. face shield*
4. visor
5. safety glasses
6. 1 or 2 or 3 or 4 or 5
7. Exp Hospitals
8. Exp Infection
9. Exp Infection Control
10. Exp Disease Transmission
11. 7 or 8 or 9 or 10
12. 6 and 11

Footwear (SICPs)

EMBASE and MEDLINE search 2000 to current

1. Shoes/
2. (shoe* adj3 cover*).mp
3. overshoe*.mp
4. over shoe*.mp
5. footwear.mp
6. shoe*.mp
7. 1 or 2 or 3 or 4 or 5 or 6
8. Exp Hospitals/
9. Exp Infections/

10. Exp Infection Control/
11. Exp Disease Transmission, Infectious/
12. 8 or 9 or 10 or 11
13. 7 and 12

Limit 13 to English language and human

CINAHL search 2000 to current

S14 S7 and S12 (English language)
S13 S7 and S12
S12 S8 or S9 or S10 or S11
S11 (MH “Disease Transmission+”)
S10 (MH “Infection Control+”)
S9 (MH “Infection+”)
S8 (MH “Hospitals+”)
S7 S1 or S2 or S3 or S4 or S5 or S6
S6 shoe*
S5 footwear
S4 over shoe*
S3 overshoe*
S2 shoe* n3 cover*
S1 (MH “Shoes”)

Gloves (SICPs)

EMBASE and MEDLINE search 2000 to current

1. Exp Gloves, Protective/
2. Exp Gloves, Surgical/
3. Glove?.mp
4. 1 or 2 or 3
5. Exp Infection/
6. Exp Infection Control/
7. Exp Cross Infection/
8. Exp Disease Transmission, Infectious/

9. 5 or 6 or 7 or 8
10. 4 and 9

Limit 10 to English language

Headwear (SICPs)

EMBASE and MEDLINE search 2000 to current

1. Head Protective Devices/
2. head wear.mp.
3. headwear.mp.
4. headgear.mp.
5. head gear.mp.
6. hat?.mp.
7. 1 or 2 or 3 or 4 or 5 or 6
8. exp Infections/
9. exp Infection Control/
10. exp Disease Transmission, Infectious/
11. exp Hospitals/
12. 8 or 9 or 10 or 11
13. 7 and 12

Limit 13 to English language

CINAHL search 2000 to current

S14 S6 AND S13 (English language)
S13 S7 OR S8 OR S9 OR S10 OR S11 OR S12
S12 (MH "Cross Infection+")
S11 (MH "Religion and Religions+")
S10 (MH "Disease Transmission+")
S9 (MH "Infection Control+")
S8 (MH "Infection+")
S7 (MH "Hospitals+")
S6 S1 OR S2 OR S3 OR S4 OR S5
S5 "headwear”

S4 headgear

S3 head wear

S2 hat?

S1 (MH "Head Protective Devices")

Surgical Face Masks (SICPs and TBPs)

EMBASE and MEDLINE search 2000 to current

1. exp Masks/
2. mask?.mp.
3. surgical mask?.mp.
4. 1 or 2 or 3
5. exp infection/
6. exp Infection Control/
7. exp Cross Infection/
8. exp Disease Transmission, Infectious/
9. transmission based precaution?.mp. (203)
10. exp infectious disease transmission, patient-to-professional/
11. ((contact or airborne or droplet) and infection$).mp.
12. ((contact or airborne or droplet) and precaution$).mp.
13. barrier precautions.mp.
14. exp Patient Isolation/
15. exp Universal Precautions/
16. enteric precautions.mp.
17. source isolation.mp.
18. isolation precautions.mp.
19. strict isolation.mp.
20. 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19
21. 4 and 20

Limit 21 to English language

Respiratory Protective Equipment (RPE) (TBPs)

EMBASE and MEDLINE search 2000 to current

1. exp Respiratory Protective Devices/
2. respiratory.mp.
3. respirators.mp.
4. FFP3.mp.
5. filtering face piece.mp.
6. filtering facepiece.mp.
7. 1 or 2 or 3 or 4or 5 or 6
8. exp Infection/
9. exp Infection Control/
10. exp Cross Infection/
11. exp Disease Transmission, Infectious
12. decontamination.mp. or Decontamination/
13. contamination.mp. or Equipment Contamination/
14. 8 or 9 or 10 or 11 or 12 or 13
15. 7 and 14

Limit 15 to English language

CINAHL search 2000 to current

S22 S7 AND S20 (English language)
S21 S7 AND S20
S20 S8 OR S9 OR S10 OR S11 OR S12 OR S13 OR S14 OR S15 OR S16 OR 17 OR S18 OR S19
S19 (MH “Bacterial Contamination”)
S18 (MH “Microbial Contamination”)
S17 "contamination”
S16 (MH “Equipment Contamination”)
S15 “decontamination”
S14 (MH “Sterilisation and Disinfection+”)
S13 (MH “Disease Transmission, Horizontal+”)
S12 (MH "Disease Transmission, Patient-to-Professional”)

S11 (MH "Disease Transmission+")

S10 (MH "Cross Infection+")

S9 (MH "Infection Control+")

S8 (MH “Infection+”)

S7 S1 OR S2 OR S3 OR S4 OR S5 OR S6

S6 "FFP3"

S5 "filtering facepiece"

S4 “filtering face piece”

S3 "respirators"

S2 "respirator"

S1 (MH “Respiratory Protective Devices")

Personal Protective Equipment (PPE) for Infectious Diseases of High Consequence (IDHC) (TBPs)

EMBASE and MEDLINE search 2000 to current

1. PPE or personal protective equipment.mp
2. coverall or suit.mp
3. glove$ or apron or visor$.mp
4. boot cover$ or over shoes or shoe cover.mp
5. surgical mask$.mp
6. respiratory protection or respirator or N95 or FFP3 or filtering face piece.mp
7. enhanced PPE or enhanced personal protective equipment.mp
8. 1 or 2 or 3 or 4 or 5 or 6 or 7
9. pandemic or epidemic.mp
10. VHF or viral haemorrhagic fever or ebola or Crimean Congo haemorrhagic fever or Marburg virus.mp
11. influenza or avian influenza.mp
12. MERS-CoV or middle eastern respiratory syndrome or coronavirus or SARS or severe acute respiratory syndrome.mp
13. smallpox or monkeypox.mp
14. nipah virus or hantavirus.mp
15. plague or Yesinia pestis.mp
16. Severe fever with thrombocytopaenia syndrome.mp

17. infectious disease$ of high consequence or high consequence infectious disease$ or high consequence infection.mp
18. 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17
19. donning or doffing or remov$.mp
20. contamination or decontamination.mp
21. competence or competency or competent.mp
22. infection control.mp
23. 19 or 20 or 21 or 22
24. 8 and 18 and 23

Limit 24 to English language

Aerosol Generating Procedures (AGPs) (TBPs)

EMBASE and MEDLINE search 2000 to current

1. exp high frequency ventilation/
2. ventilation, mechanical.mp
3. intubation, intratracheal/
4. Endotracheal intubation.mp.
5. Tracheostomy.mp.
6. bronchoscopy.mp.
7. (Nebuli*ation or nebuli*e).mp.
8. (Sputum adj2 induction).mp.
9. (Oxygen adj2 therapy).mp.
10. (Autopsy or Post-mortem).mp.
11. ((Respiratory or airway or air way or open) adj3 suction*).mp.
12. Heat moisture exchange.mp.
13. thoracostomy.mp.
14. ((chest adj3 physiotherapy) or (chest adj3 physical therapy)).mp.
15. (sputum adj3 (induction or inducing)).mp.
16. (lung function test* or pulmonary function test*).mp.
17. exp cardiopulmonary resuscitation/
18. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17
19. aerosol generating procedure.tw.
20. aerosol generating procedure*.mp.

21. (aerosol adj3 procedure).mp.
22. (aerosol or airborne or airbourne).mp.
23. Occupational exposure.mp.
24. Infectious disease transmission.mp.
25. Airborne infection.mp.
26. Infection control.mp.
27. Infection control, dental.mp.
28. exp cross infection/
29. Disease outbreaks.mp.
30. Disease transmission.mp.
31. Aerosol*.mp.
32. 19 or 20 or 21 or 22 or 25 or 31
33. 18 and 32
34. 23 or 24 or 26 or 28 or 29 or 30 or 33
35. 18 and 32 and 34
36. limit 35 to english language
37. limit 36 to human
38. limit 37 to humans

CINAHL search 2000 to current

S20 Limit to English language
S19 S17 AND S18
S18 S12 OR S14 OR S15 OR S16
S17 S1 OR S2 OR S3 OR S4 OR S5 OR S6 OR S7 OR S8 OR S9 OR S10 OR S11 OR S13
S16 "exp infection control" OR (MH "Infection Control+") OR (MH "Cross Infection+")
S15 (MM "Occupational Exposure")
S14 "airborne"
S13 (MH "Ultrasonic Surgical Procedures+")
S12 "aerosol generating procedure" OR (MM "Aerosols")
S11 (MH "Resuscitation, Cardiopulmonary") OR (MH "Bystander CPR") OR "cardiopulmonary resuscitation"

S10 (MH "Chest Physical Therapy") OR (MH "Chest Physiotherapy (Iowa NIC)") OR (MH "Chest Physiotherapy (Saba CCC)") OR "chest physiotherapy or chest physical therapy"

S9 "Autopsy or Postmortem"

S8 (MH "Sputum") OR "induction of sputum or sputum induction"

S7 (MH "Nebulizers and Vaporizers") OR (MH "Bronchial Provocation Tests") OR "Nebulisation or nebulise or nebulization or nebulize" S6 (MH "Bronchoscopy") OR "bronchoscopy"

S5 (MH "Thoracostomy")

S4 (MH "Tracheostomy") OR "tracheostomoy"

S3 (MH "Intubation, Intratracheal+") OR (MH "Intubation+") OR (MH "Tube Removal") OR (MH "Laryngeal Masks") OR (MH "Extubation")

S2 (MH "Ventilation, High Frequency+") OR (MM "Ventilators, Mechanical") OR (MH "Positive Pressure Ventilation+") OR (MH "Tracheostomy and Ventilator Swallowing and Speaking Valve") OR (MH "Ventilation, Manual") OR (MH "Ventilation, Negative Pressure") OR (MM "Intermittent Positive Pressure Ventilation") OR (MH "Respiration, Artificial+")

S1 (MH "Ventilation, High Frequency+")

Management of Blood and Body Fluid Spillages (SICPs)

MEDLINE search 2020 to current

1. exp Blood/
2. exp Body Fluids/
3. exp Feces/
4. exp Urine/
5. exp Bodily Secretions/
6. exp Vaginal Discharge/
7. 1 or 2 or 3 or 4 or 5 or 6
8. exp Disinfection/
9. exp Decontamination/
10. exp Disinfectants/
11. housekeeping, hospital/ or laundry service, hospital/
12. Occupational Exposure/pc [Prevention & Control]

13. clean*.mp
14. exp Universal Precautions/
15. 8 or 9 or 10 or 11 or 12 or 13 or 14
16. 7 and 15

Limit 16 to English language

EMBASE search 2000 to current

1. exp blood/
2. exp body fluid/
3. exp urine/
4. exp feces/
5. exp bodily secretions/
6. bodily secretions.mp.
7. bodily fluids.mp.
8. 1 or 2 or 3 or 4 or 5 or 6 or 7
9. occupational exposure/pc [Prevention]
10. exp disinfection/
11. exp disinfectant agent/
12. exp decontamination/
13. exp detergent/
14. exp hospital service/
15. exp laundry/
16. exp cleaning/
17. domestic chemical/
18. housekeeping/
19. clean*.mp.
20. 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19
21. 8 and 20
22. exp animals/ not humans
23. 21 NOT 22
24. limit 23 to (conference abstract or letter)
25. 23 NOT 24

Limit 25 to English language

CINAHL search 2000 to current

S24 S8 AND S21 (Limit year 2000 to 2019)
S23 S8 AND S21 (English language)
S22 S8 AND S21
S21 S8 OR S10 OR S11 OR S12 OR S13 OR S14 OR S15 OR S16 OR S17 OR S18 OR S19 OR S20
S20 (MH “Mandatory Reporting”) OR “mandatory requirements”
S19 (MH “Policy and Procedure Manuals”)
S18 (MH “Hospital Policies+”)
S17 (MH "Legislation") OR (MH “Government Publications”) OR (MH “Grey Literature”)
S16 “clean*”
S15 (MH “Housekeeping Department”) OR (MH “Laundry Department”)
S14 (MH “Disinfectants”)
S13 (MH “Cleaning Compounds”)
S12 “spillage*”
S11 (MH "Occupational Exposure/PC")
S10 (MH "Sterilisation and Disinfection+")
S9 (MH "Universal Precautions")
S8 S1 OR S2 OR S3 OR S4 OR S5 OR S6 OR S7
S7 vaginal discharge
S6 bodily fluids
S5 “bodily secretions”
S4 (MH “Feces+”)
S3 (MH "Urine")
S2 (MH "Body Fluids+")
S1 (MH “Blood+")

Occupational Exposure Management (including sharps) (SICPs)

EMBASE and MEDLINE search 2000 to current

1. Exp Needlestick Injuries/
2. Exp Occupational Exposure/
3. (sharp? adj3 injur*).mp
4. 1 or 2 or 3

5. Exp Accident Prevention/
6. Exp Infection Control/
7. Exp Infection Control/ Exp Infections/
8. (safe* adj2 practice*).
9. Infectious Disease Transmission, Patient-to-Professional/
10. Exp Infectious Disease Transmission, Patient-to-Professional/ Exp Blood-Borne Pathogens/
11. 5 or 6 or 7 or 8 or 9 or 10
12. 4 and 11

Limit 12 to English language

CINAHL

1. (MH “Sharps Injuries+”)
2. (MH “Occupational Exposure”)
3. Sharp* N3 injur*
4. 1 or 2 or 3
5. (MH “Safety+”)
6. (MH “Infection Control+”)
7. (MH “Infection+”)
8. Safe* N2 practice”
9. (MH “Disease Transmission, Patient-to-Professional”)
10. 5 or 6 or 7 or 8 or 9
11. 4 and 10

Safe Management of Linen (SICPs and TBPs)

MEDLINE and EMBASE search 2000 to current

1. Exp “Bedding and Linens”/
2. linen*.mp
3. bedding*.mp
4. 1 or 2 or 3
5. Laundering/
6. Laundry Service, Hospital/

7. laundr*.mp
8. launder*.mp
9. exp Hospitals/
10. exp Infections/
11. exp Infection Control/
12. exp Disease Transmission, Infectious/
13. 5 or 6 or 7 or 8
14. 9 or 10 or 11 or 12
15. 4 and 13 or 14

Limit 15 to English language

Safe Disposal of Waste (SICPs)

EMBASE and MEDLINE search 2000 to current

1. exp Medical Waste/
2. exp Hazardous Waste/
3. exp Refuse Disposal/
4. exp Waste Disposal, Fluid/
5. exp Waste Management/
6. exp Medical Waste Disposal/
7. clinical waste.mp.
8. health* waste.mp.
9. sharp* disposal.mp.
10. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9
11. exp Hospitals/
12. exp Infection/
13. exp Infection Contol/
14. exp Cross Infection/
15. exp Transportation/
16. exp Disease Transmission, Infectious/
17. 11 or 12 or 13 or 14 or 15 or 16
18. 10 and 17

Limit 18 to English language

CINAHL search 2000 to current

S17 S8 AND S15 English Language
S16 S8 AND S15
S15 S9 OR S10 OR S11 OR S12 OR S13 OR S14
S14 (MH "Transportation+")
S13 (MH "Communicable Diseases+")
S12 (MH "Cross Infection+")
S11 (MH "Infection Control+")
S10 (MH "Infection+")
S9 (MH "Hospitals+")
S8 S1 OR S2 OR S3 OR S4 OR S5 OR S6 OR S7
S7 "health* waste"
S6 "clinical waste"
S5 "waste management"
S4 (MH "Sharps Disposal")
S3 (MH "Medical Waste Disposal")
S2 (MH "Medical Waste+")
S1 (MH "Hazardous Materials")

Cough Etiquette/Respiratory Hygiene (SICPs)

MEDLINE search 2015 to current

1. Exp cough/
2. Exp sneezing/
3. Cough etiquette.mp
4. Respiratory hygiene.mp
5. 1 or 2 or 3 or 4
6. Exp Hand hygiene/
7. Exp Infection Control/
8. Exp Cross Infection/
9. Exp Disease Transmission, Infectious/
10. 6 or 7 or 8 or 9
11. 5 and 10

Limit 11 to English language

EMBASE search 2015 to current

1. Exp coughing/
2. Exp sneezing/
3. Cough etiquette.mp
4. Respiratory hygiene.mp
5. 1 or 2 or 3 or 4
6. Exp hand washing/
7. Exp infection control/
8. Exp cross infection/
9. Exp disease transmission/
10. 6 or 7 or 8 or 9
11. 5 and 10

Limit 11 to English language

CINAHL searched 2015 to current

S11 S5 and S10 English language and human
S10 S6 or S7 or S8 or S9
S9 (MH"Disease Transmission+")
S8 (MH"Cross Infection+")
S7 (MH"Infection Control+")
S6 (MH"Handwashing+")
S5 S1 or S2 or S3 or S4
S4 "Respiratory hygiene"
S3 "Cough etiquette"
S2 (MH"Sneezing")
S1 (MH"Cough")

Patient Placement, Isolation, and Cohorting

Patient Placement Isolation and Cohorting (SICPs)

MEDLINE search 17th July 2018 to current

1. exp patient isolation/
2. exp hospitals, isolation/
3. cohorting.mp.
4. (EXP RESIDENTIAL FACILITIES/ OR EXP HOME CARE SERVICES/) AND ISOLATION.MP
5. exp patients' rooms/
6. single room?.mp.
7. side room?.mp.
8. 1 or 2 or 3 or 4 or 5 or 6 or 7
9. exp infections/
10. exp disease transmission, infectious/
11. exp universal precautions/
12. exp infection control/
13. 9 or 10 or 11 or 12
14. 8 and 13

Limit 14 to English language and humans

EMBASE search 17th July 2018 to current

1. exp patient isolation/
2. exp hospitals, isolation/
3. cohorting.mp.
4. (EXP RESIDENTIAL FACILITIES/ OR EXP HOME CARE SERVICES/) AND ISOLATION.MP
5. exp patients' rooms/
6. single room?.mp.
7. side room?.mp.
8. 1 or 2 or 3 or 4 or 5 or 6 or 7
9. exp infections/
10. exp disease transmission, infectious/

11. exp universal precautions/
12. exp infection control/
13. 9 or 10 or 11 or 12
14. 8 and 13 English language and humans

Limit 14 to (English language and humans)

CINAHL search 17th July 2018 to current

S13 S11 and S12 (Limit to English language and exclude Medline results)
S12 S7 or S8 or S9 or S10
S11 S1 or S2 or S3 or S4 or S5 or S6
S10 (MH “Infection Control+”)
S9 TX universal precautions
S8 (MH “Disease Transmission+”)
S7 (MH “Infection+”)
S6 TX single room
S5 TX side room
S4 (MH “Patients' Rooms+")
S3 TX cohorting
S2 (MH "HOSPITALS+" AND "ISOLATION") OR (MH "RESIDENTIAL FACILITIES+" AND "ISOLATION")
S1 (MH "Patient Isolation+")

Infection Prevention and Control during Care of the Deceased (TBPs)

Ovid MEDLINE(R) ALL <2000 to current>

1 exp Cadaver/
2 cadaver*.ti,ab.
3 decedent*.ti,ab.
4 deceased*.ti,ab.
5 last offices.ti,ab.
6 hygienic preparation*.ti,ab.
7 exp Funeral Rites/
8 funer*.ti,ab.

9 (care adj3 (after death or post-death or following death)).ti,ab.
10 Mortuary Practice/
11 mortuar*.ti,ab.
12 mortem*.ti,ab.
13 embalm*.ti,ab.
14 ((body or cadaver) adj1 bag*).ti,ab.
15 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14
16 Infections/ or cross infection/
17 *Infection Control/
18 (infect* adj2 (prevention or control)).ti,ab.
19 IPC.ti,ab.
20 exp Disease Transmission, Infectious/
21 (disease* adj2 transmi*).ti,ab.
22 16 or 17 or 18 or 19 or 20 or 21
23 15 and 22
24 limit 23 to english language

Embase

1. exp Cadaver/
2. cadaver*.ti,ab.
3. decedent*.ti,ab.
4. deceased*.ti,ab.
5. last offices.ti,ab.
6. hygienic preparation*.ti,ab.
7. exp posthumous care/
8. funer*.ti,ab.
9. (care adj3 (after death or post-death or following death)).ti,ab.
10. mortuar*.ti,ab.
11. mortem*.ti,ab.
12. embalm*.ti,ab.
13. ((body or cadaver) adj1 bag*).ti,ab.
14. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13
15. infection/ or cross infection/
16. *Infection Control/

17. (infect* adj2 (prevention or control)).ti,ab.
18. IPC.ti,ab.
19. exp Disease Transmission/
20. (disease* adj2 transmi*).ti,ab.
21. 15 or 16 or 17 or 18 or 19 or 20
22. (14 and 21) not conference*.so,pt.
23. limit 22 to english language
24. limit 23 to yr="2000 -Current"

CINAHL

S1 (MH "Cadaver+")
S2 TI cadaver* OR AB cadaver*
S3 TI decedent* OR ABdecedent*
S4 TI deceased* OR ABdeceased*
S5 TI last offices OR AB last offices
S6 TI hygienic preparation* OR AB hygienic preparation*
S7 (MH "Burial Practices")
S8 TI funer* OR AB funer*
S9 TI (care N3 (after death or post-death or following death)) OR AB (care N3 (after death or post-death or following death))
S10 (MH "Postmortem Care")
S11 TI mortuar* OR AB mortuar*
S12 TI mortem* OR AB mortem*
S13 TI embalm* OR AB embalm*
S14 TI ((body or cadaver) N1 bag*) OR AB ((body or cadaver) N1 bag*)
S15 S1 OR S2 OR S3 OR S4 OR S5 OR S6 OR S7 OR S8 OR S9 OR S10 OR S11 OR S12 OR S13 OR S14
S16 (MH "Infection Control+")
S18 TI (infect* N2 (prevention or control)) OR AB (infect* N2 (prevention or control))
S19 TI IPC OR AB IPC
S20 (MH "Disease Transmission+")
S21 TI (disease* N2 transmi*) OR AB (disease* N2 transmi*)
S22 S16 OR S17 OR S18 OR S19 OR S20 OR S21
S23 S15 AND S22

S24 S15 AND S22

Narrow by Language: - English

Management of Incidents and Outbreaks in Neonatal Units (NNUs)

EMBASE and MEDLINE search 2000 to current

1. (neonat* or NICU or newborn or preterm or premature)
2. (outbreak adj3 prevention).mp
3. (outbreak adj3 management).mp
4. (outbreak adj3 control).mp
5. (outbreak adj3 reporting).mp
6. (outbreak adj3 investigation).mp
7. 2 or 3 or 4 or 5 or 6
8. 1 and 7

Limit 8 to English language

Definitions of Transmission Based Precautions (TBPs)

MEDLINE and EMBASE search 2000 to current

1. "transmission based precaution*".mp.
2. "additional infection control*".mp.
3. "airborne transmission*".mp.
4. "droplet transmission*".mp.
5. "contact transmission*".mp.
6. airborne.mp.
7. droplet*.mp.
8. "contact precaution*".mp.
9. exp Aerosols/
10. aerosol*.mp.
11. exp Infection Control/
12. exp Infections/
13. exp Disease Transmission, Infectious/
14. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10
15. 11 or 12 or 13

16. 14 and 15

Limit 16 to English language

Healthcare Infection Incidents and Outbreaks in NHSScotland

Existing legislation and recent (<1 year) guidance was available to answer all research questions for this review and so no search strategy was required.

Appendix 6: Comparison of single-person and two-person methodology

Protocol/methodology	Single-person review	Two-person systematic review
Development of research questions	No difference	No difference
Identifying evidence	Lead reviewer only	Both reviewers independently select articles for inclusion and agree by discussion
Evidence appraisal and grading	Lead reviewer only	Lead reviewer appraises all evidence and completes evidence tables, second review completes a check of at least 30% of the appraisals and evidence tables
Development of recommendations	Lead reviewer suggests recommendations for Sign-off by the NCIC	Lead reviewer suggests recommendations, second author agrees the content before sign-off by the NCIC,
Consultation	No difference	No difference
Development of the NIPCM	No difference	No difference
Development of supporting tools	No difference	No difference
Maintaining and updating the NIPCM	No difference	No difference
Presentation of guidance	No difference	No difference

NHSScotland Assure Research Service

Applications are now open for a £1.55m research and innovation budget, administered by Edinburgh Napier University, on behalf of NHSScotland Assure.

You can learn more below and **register to attend upcoming events**, where you can also find recorded materials from past events.

The NHSScotland Assure Research Service's remit is to achieve a coordinated portfolio, supporting the development of evidence-based guidance, to deliver safe healthcare environments that are free from avoidable risk. The service will seek to ensure that the most up to date and robust research is translated into practice as new and emerging evidence becomes available.

Find out more about the following:

Background

NHSScotland Assure was launched as part of National Services Scotland (NSS), 1st June 2021. It underpins a transformation in the approach to promoting excellence, reducing risks in the healthcare-built environment and ensuring healthcare facilities are safe, fit for purpose, cost effective and capable of delivering sustainable services over the long term.

In this context, risks refer to those commonly associated with service systems, that is, the provision of water and drainage, air ventilation, electricity, fire prevention and medical gases, with infection prevention and control as a consideration for each to support better outcomes for the population. This is achieved through the provision of expertise and evidence-based advice and guidance that contributes to reducing risk, delivering a sustainable healthcare service, and improving the healthcare experience for Scotland.

Guidance aims to provide advice on how to mitigate risks problems or difficulties and, to enable successful outcomes in the context of the NHS and the planning, design, construction and maintenance of its healthcare environment.

What kind of research will be funded?

The fund will ensure that the most up-to-date and robust research and innovation is translated into practice to improve future health outcomes worldwide. The outcomes must benefit NHSScotland and align with the key priorities of NHSScotland Assure.

Over the duration of the fund, the team are looking for applications and impactful research in the following areas:

- Water systems, including drainage (design, installation, commissioning and maintenance (DICM))
- Ventilation systems (DICM)
- Pathogens, the microbiome, AMR, transmission risks and burden of disease in the hospital environment
- Hospital design, including size and single room provision
- Lessons learned from COVID-19
- Human factors/Ergonomics and Infection Prevention and Control
- Climate change requirements and the unintended consequences on built environment risks.
- The role of safety and harms in relation to medical gases, electrical systems and fire safety.

Please review the additional content on **Scope (/research-and-innovation/business-and-innovation-hub/innovate-with-us/joint-research-and-innovation/funding-support/nhsscotland-assure-research-service/nhsscotland-assure-research-funding-scope)** before proceeding.

Scope

Research should provide new evidence which supports extant or alternative methodologies for complying with guidance by more effective or efficient means. More information on the research themes envisaged for funding can be read under **Scope (/research-and-innovation/business-and-innovation-hub/innovate-with-us/joint-research-and-innovation/funding-support/nhsscotland-assure-research-service/nhsscotland-assure-research-funding-scope)**.

Who can apply?

The fund is open to researchers from any country who are looking at ways to deliver safe healthcare environments that are free from avoidable risk. We are particularly interested in applications from consortia and inter-disciplinary teams, though applications from individuals are equally welcome.

We want to nurture an inclusive approach between professional roles within the built environment and across infection, prevention & control (IP&C); healthcare providers; academia; research institutions; and business and industry.

What are the objectives?

The NHSScotland Assure Research, Development and Innovation service (https://www.nss.nhs.scot/browse/nhs-scotland-assure/research-development-and-innovation) is a service whose remit is to achieve a coordinated research portfolio, supporting the development of evidence-based guidance and research, to deliver safe healthcare environments that are free from avoidable risk. Further to the above, the service will seek to ensure that the most up to date and robust research is translated into practice as new and emerging evidence become available.

NHSScotland Assure seeks to implement processes and procedures to achieve the following;

- increased evidence base in built environment research by stimulating excellent applied and translational research.
- establish critical mass and promote knowledge sharing between investigators by creating a focused internationally competitive multidisciplinary, multi-organisational group, supporting state-of-the-art research excellence.
- increased training, provide support for additional research posts at all levels, promote research career development and extend expertise in research design and methodology.
- promoting and support of research leadership and mentoring.

The service will commission, tender and disseminate research worldwide. This will not only support NHSScotland Health Boards to increase their knowledge to manage built environment risks but will also ensure Scotland is recognised internationally as an expert in the field.

How to apply

The next closing date for the fund is **31st May 2024**.

Applicants should download the **Application Form (/-/media/documents/nhsscotland-assure-research-funding-application-form-v5.ashx)** and read the associated **Guidelines for the Application Form (/research-and-innovation/business-and-innovation-hub/innovate-with-us/joint-research-and-innovation/funding-support/nhsscotland-assure-research-service/nhsscotland-assure-research-application-guidlines)**. The guidelines provide details on how to complete each section of the Application Form.

The Application Form and Guidelines may have changed from previous versions, so applicants are urged to read and adhere to the correct version.

Completed Application Forms for Round 6 should be submitted to **NHSAResearchService@napier.ac.uk (mailto:NHSAResearchService@napier.ac.uk) by 31st May 2024**.

Additional information for Applicants can be found here (/research-and-innovation/business-and-innovation-hub/innovate-with-us/joint-research-and-innovation/funding-support/nhsscotland-assure-research-service/nhsscotland-assure-additional-information) and should you have any enquiries please contact NHSAResearchService@napier.ac.uk (mailto:NHSAResearchService@napier.ac.uk).

Events

8 May Noon-1pm - Round 6 Drop-in Session for potential applicants > **Register (https://www.tickettailor.com/events/edinburghnapieruniversityinnovationhub/1236595)**

The Edinburgh Napier Project team has run events throughout the duration of the fund.

Past Events

29 November 2023 - Lunch & Learn for anyone interested in applying under Round 5

Watch now: **NHSScotland Assure Research Fund R5 Lunch & Learn Nov 2023 (https://www.youtube.com/watch?v=wRyCx0F4gVU&feature=youtu.be)**

Additional materials:

- **NHSScotland Assure Research Service Overview (/-/media/dual-career/20231122-nhsscotland-assure-research-fund-relaunch-slides-pdf-v10.ashx)**
- **NHSScotland Assure Research Service Fund: Project & Process Information (/-/media/dual-career/enu-nhs-assure-relaunch-ll-l-johnston.ashx)**

24 June 2022 - Launch Event

Note that the application process and guidance provided to applicants at the time of the following events is not accurate after 01 October 2023.

Please refer to the process and scope outlined ABOVE for all applications to the Fund after 01 October 2023.

To review the content of a past event, click on the relevant link below.

24 June 2022 - Launch Event Materials (/research-and-innovation/business-and-innovation-hub/innovate-with-us/joint-research-and-innovation/funding-support/nhsscotland-assure-research-service/event)

Contact Us

If you have any questions or for more information, please contact us on NHSAResearchService@napier.ac.uk

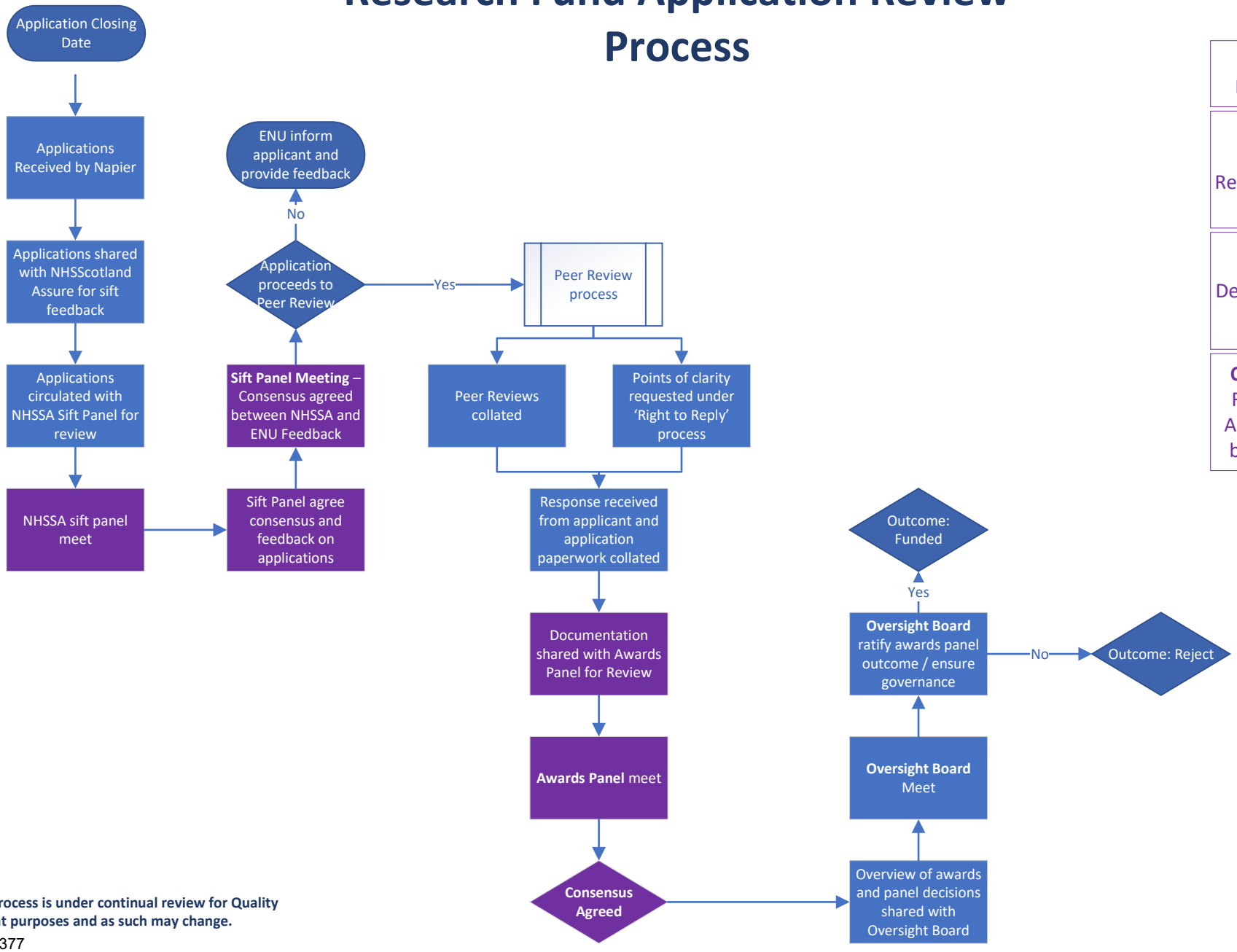
Contact us (mailto: NHSAResearchService@napier.ac.uk?subject=NHS%20Scotland%20Assure%20Research%20Application)

(/)

NHS Scotland Assure
Quality in the healthcare environment

Edinburgh Napier University – NHSSA Research Fund Application Review Process

NHS National Services Scotland



Roles and Responsibilites

Sift Panel
Review Applications

Awards Panel
Decide outcomes of applications

Oversight Board
Ratify outcomes
Authorise funding based on budget

Please note – this process is under continual review for Quality Improvement purposes and as such may change.

A48891377

Research portfolio

Published on 22 May 2024

Development of research portfolio

NHS Scotland Assure is adding to the knowledge base available to built environment projects. Building on this existing knowledge will reduce risks, increase quality and promote the sharing of research with key stakeholders. Working with external stakeholders and other Assure services will ensure information and evidence-based guidance is available to those who need it.

This service identifies key topics relating to reduction of risk in the built environment by engaging with stakeholders, other NHS Scotland Assure services and using lessons learned.

The service prioritises research themes and needs in line with the service strategy and identifies opportunities for research and sharing findings.

Commissioning Partnership with Edinburgh Napier University

NHS Scotland Assure appointed Edinburgh Napier University in April 2022 to oversee and manage a fund in excess of £1,000,000 focused on developing international best practice in the built environment for healthcare. The fund is open and scheduled to run until March 2025.

This research partnership aims to provide opportunities to explore development of a consortium of different disciplines that deliver research in line with the identified needs of NHS Scotland Assure. The service will share best practice case studies in standards and models for the built environment.

Further information on the fund including how to apply, future closing dates and events and relevant contact details can be found on the Edinburgh Napier website.

Completed Projects

- **CoEResearch-0001: Investigate the prevalence and concentration of Cupriavidus and other Opportunistic Premise Plumbing Pathogens (OPPPs) in healthcare water systems across Scotland and England.**

Chief Investigator: Dr Teresa Inkster, NHS Greater Glasgow & Clyde.

Read the report
Read our research Q&A with Dr Teresa Inkster, which talks about why the research is needed, what it set out to achieve, what impact it will have on existing guidance and more. You can also find an interview with the Chief Investigator here.

- **CoEResearch-0002: Hospital sinks and drains as a source of antimicrobial resistant microorganisms: studies to investigate colonisation, dispersal and decontamination.**

Chief Investigator: Dr Ginny Moore, UK Health Security Agency (UKHSA).
Read the report
Read our research Q&A with Dr Ginny Moore, which talks about why the research is needed, what it set out to achieve, what impact it will have on existing guidance and more.

- **AssureResearch21-0001 Far UVC light for reducing airborne transmission of bacteria and viruses.**

Chief Investigator: Dr Kenneth Wood, St Andrew's University.
Read the report
Supporting Institutions: University of Leeds, Ninewells Hospital, NHS Tayside & Columbia University.

- **AssureResearch21-0002 Efficacy of hand hygiene wipes active against spore forming bacteria and the use of wipes as a substitute for soap and water for performing hand hygiene in healthcare settings.**

Chief Investigator: Dr Teresa Inkster, NHS Greater Glasgow & Clyde.

Research currently underway

- **CoEResearch003: Whole genome sequencing of potable water derived Cupriavidus species.**

Chief Investigator: Professor Alistair Leanord, Scottish Microbiology. Reference Laboratory, Glasgow.

- **AssureResearch21-0003: Development of laboratory methodology to identify opportunistic premise plumbing pathogens other than Legionella and Pseudomonas aeruginosa from hospital water systems.**

Chief Investigator: Dr Teresa Inkster, NHS Greater Glasgow & Clyde.

Get in touch

Contact us to find out more about how our research portfolios can help your project.

Directorate of the Chief Operating Officer, NHS Scotland
Healthcare, Quality and Improvement Division

Scottish Government
Riaghaltas na h-Alba
gov.scot

Dear Colleagues,

NHS SCOTLAND INFECTION PREVENTION AND CONTROL (IPC) ROLES AND RESPONSIBILITIES, INCLUDING IPC TEAM (IPCT) AND SPECIALIST IPC ROLE DESCRIPTORS.

This letter replaces the previous HDL (2005) 8 and builds on evidence and lessons learnt following: The Vale of Leven Hospital Inquiry Report (2014), The Queen Elizabeth University Hospital Review (2020) and The Queen Elizabeth University Hospital/ NHS Greater Glasgow and Clyde Oversight Board: Final Report (2021) . It outlines the main responsibilities for Boards in relation to the infection prevention and control (IPC) service and introduces the team and specialist IPC role descriptors.

The Role of the Chief Executive

The Chief Executive is ultimately responsible for ensuring successful prevention and control of infections within their NHS Board area. This accountability requires that the Chief Executive:

- Is aware of their legal responsibilities to identify, assess and control risks of infection in the workplace,
- Appoints an Executive Lead to be the Healthcare Associated Infection (HAI) Executive Lead,
- Appoints either a Clinical Lead and/or Infection Control Manager to have responsibility for the IPC service with sufficient resource to provide IPC support and advice and is able to demonstrate clear lines of governance throughout the organisation, and
- Ensures that prevention and control of infection is a core part of their organisation's clinical

From the Interim Chief Nursing Officer

Anne Armstrong

02 May 2024

DL (2024) 11

Addresses

For action

NHS Scotland Chairs,
NHS Scotland Chief Executives,
Chief Officers Health and Social Care Partnerships,
Local Authorities,
HR Directors,
Medical Directors,
Nurse Directors,
Primary Care Leads,
Directors of Pharmacy,
Directors of Public Health,
Directors of Dentistry,
Optometric Advisors,
All Independent Contractors (Dental, Pharmacy, General Practice and Optometry),
Infection Control Managers,
Infection Control Doctors,
Infection Control Nurses.

Further Enquiries

Scottish Government Directorate for Chief Nursing Officer

Email: cno@gov.scot

governance and patient safety programmes.

Role of Healthcare Associated Infection (HAI) Executive Lead

The HAI Executive Lead holds delegated accountability for the IPC service function within their portfolio answering directly to the Chief Executive in line with the Board's internal scheme of delegation. HAI Executive Leads are responsible for:

- Annual workforce planning to establish an IPCT appropriate to the size and complexity of the Board, in line with the requirements of the Health and Care (Staffing) (Scotland) Act 2019,
- Responsible for the management of any IPC associated risks which have been escalated to ensure appropriate mitigation steps are taken,
- Ensure the IPC service can provide the function required and have an appropriate work programme which supports provision and continuous improvement, and
- Responsible for chairing the NHS Healthcare Associated Infection Executive Committee (HAIEC)/ Infection Control Committee (ICC)
- Oversee and ensure relevant and required IPC/ healthcare associated infection (HCAI) reports are published and/or sent to the appropriate National Board/Scottish Government.

Infection Control Manager and/or Clinical Lead

The Infection Prevention Workforce: Strategic Plan (2022-2024) and accompanying CNO letter states that both the complexity and size of the Board should be considered when determining whether there is a need for a dedicated IPC Clinical Lead.

The Clinical Lead role **may not be required in all boards** and is distinct from the role of the HAI Executive Lead which will retain the delegated accountability within the Board for HAI.

Team and Specialist IPC Role Descriptors:

The Infection Prevention and Control Team (IPCT)

The function of the IPCT is to advise on the prevention, surveillance, investigation, and control of infection across health and care settings in collaboration with other key service partners. The IPCT works collaboratively with microbiology, virology and other services and departments, including operational and senior management teams, health protection teams, care home providers and the health and social care partnerships , to provide infection, prevention, and control (IPC) subject matter expertise, safe, effective, and person-centred communications and advice and support to help reduce the risk of infection to patients, service users, staff and visitors.

The membership, structure, and scope of an IPCT should reflect the geography, function, size, and complexity of the NHS Board it serves.

A descriptor of an IPCT can be found in ANNEX A.

IPC Specialist Role Descriptors

Since the publication of the Infection Prevention Workforce Strategic Plan 2022- 2024 in December 2022, the Healthcare Associated Infection (HCAI) and Antimicrobial Resistance (AMR) Policy Unit has been engaging with national and territorial Boards to produce a Clinical Lead role descriptor for Scotland and update the existing Infection Control Manager (ICM) descriptor within HDL(2005)8.

During the first stage of engagement with IPCTs from across Scotland, the HCAI/AMR Policy Unit was asked by key stakeholders to develop role descriptors for Infection Control Doctors, Nurses/Practitioners and Infection Control Support Workers.

ANNEX B holds role descriptors for all of the aforementioned team members. It is recognised that some staff may have additional responsibilities based on local need which would not necessarily be considered as a core responsibility for that role across Scotland, and therefore such responsibilities are not included within the descriptors.

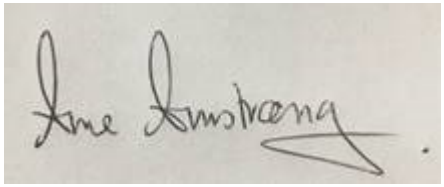
The individual role and team descriptors outline the main responsibilities for IPC specialists across Scotland. The

individual role descriptors were developed with an initial draft created by NHS Education for Scotland, based on current job descriptions for IPC posts across Scotland and England, which was followed by consultation with NHS Scotland IPC staff representatives, HAI Executive Leads and Scottish Government Professional Advisors**.**

All descriptors emphasise that IPC teams are responsible for the provision of IPC advice to other areas and departments, noting that this does not mean they are accountable for IPC practice in those areas.

The IPCT and team member descriptors **are not mandatory**. They have been developed as a support tool and guide for Boards to refer to when reviewing local roles or IPCT structures as part of workforce planning in line with the requirements of the Health and Care (Staffing) (Scotland) Act 2019.

Yours sincerely,



Anne Armstrong
INTERIM CHIEF NURSING OFFICER

Annex A – IPCT DESCRIPTOR

IPC Team Descriptor ANNEX A.docx

Annex B – SPECIALIST ROLE DESCRIPTORS – CROSS READ TABLE

Role Descriptors - Cross Read Table ANN

Key Stage Assurance Review (KSAR):

Notes for Board Infection Prevention and Control Teams

Version 1.0

July 2023

A48891377

Contents

Introduction

The overarching emphasis of any Key Stage Assurance Review (KSAR) is **assurance**. An NHS board has a duty to ensure that the premises within which it provides healthcare are safe. NHS boards should during the planning and execution of construction projects assure themselves that governance systems and reporting structures are robust, and that the board can demonstrate a transparent Infection Prevention and Control (IPC) assurance and accountability framework through those processes. The board will provide project documentation during the KSAR as evidence to NHS Scotland Assure (NHSSA) to demonstrate the processes in place to meet the requirements for the KSAR review. The information suggested in this document, like the KSAR workbooks, is not prescriptive as local NHS boards will have their own processes for projects management and governance and so should assess the evidence they possess which may provide evidence to support the KSAR review.

To demonstrate active collaboration between the Project Team and the Board IPC team it is important that information flows freely and timeously between teams. NHSSA will look at who is providing IPC advice, what experience or qualifications they have in the IPC role with respect to the built environment, and how they receive the technical/advisory support they need (for example from mechanical, electrical, and plumbing specialists or more experienced members of the IPC Team).

For assurance that the IPC Team can provide ongoing specialist support and active involvement for the project throughout its lifespan we will ask the project and IPC Team about quantification of the allocated IPC provision, workforce capacity and resilience arrangements.

Key stage assurance reviews (KSARs) are carried out at the following key stages of the project's development.

1. Outline business case (OBC)
2. Full business case (FBC)
3. Construction
4. Commissioning
5. Handover

The NHSSA team will ask for evidence to be provided for each review. Workbooks for each KSAR will list the specific areas that we are looking at within different elements of the project and suggest the evidence that could be used to demonstrate assurance. For example, one area highlighted in the IPC section asks how the board demonstrates that it has an effective IPC management structure in place and suggests the IPC Team structure as one piece of evidence to be provided. Because some elements are checked at more than one review, some of the evidence may be asked for multiple times. It is worth keeping a folder with everything submitted to any prior review, but remember to update anything that has changed, particularly anything that has changed because of a previous review.

The KSAR workbooks are being continually reviewed and may have been updated since any previous review. NHSSA will share the most up to date version of the workbook with the Board Project Team in advance of the KSAR which should be shared with the Board IPC Lead/s. If you haven't been given one, please ask your Project lead.

Pre-KSAR

The NHSSA IPC Lead will make contact with the board IPCT in advance of a KSAR commencing. The pre-meet will allow for discussions generally regarding the project, the KSAR workbook requirements for the Board IPC team and any IPC issues identified by the local board.

IPC workshop

After the local board has submitted evidence to support the KSAR requirements the NHSSA team will commence their review. During this time workshops are held for all the disciplines including IPC. This meeting allows any observations by the NHSSA IPC lead (or other technical leads) to be discussed in detail.

Listed below are examples of the evidence that could be needed at each KSAR. It is not exclusive, and your board may have different documents or systems which will provide the relevant evidence. It helps if you can familiarise yourself with the workbook for your current KSAR. Remember that you can always ask the NHSSA IPC Lead aligned to your KSAR for advice on what evidence to provide.

Evidence requested for every KSAR

Board IPCT structure

- This may be part of an IPC Policy or a stand-alone document. Ideally it will show who is the health board IPC lead/s for the project and the reporting and management relationships within IPC and project governance structures. This should include the board IPC lead/s who may be involved.
- Evidence of the suitability of the board project IPC lead/s assigned to the project to undertake that role at all stages of the project, for example work experience gained from active participation in similar projects or qualifications in IPC and the built environment. If the IPC lead/s assigned to the project is less experienced, there should be details of how they are being supported and developed to undertake that role.

Board IPC Strategy

- This may be part of an IPC Policy or a stand-alone document. It should demonstrate the board's multidisciplinary approach to IPC and should include all capital projects. It should include the current IPC assurance and accountability framework (or equivalent local governance and assurance arrangements for the IPC programme and capital projects).

Board Annual Programme for IPC

- This should demonstrate that the necessary board IPC input into capital projects has been planned and included in the annual IPC programme and can be adequately resourced in terms of staff time and expertise. Additional detail around any additional IPC resource or clinical backfill requirements for major and long-term projects is helpful.

Project Team Structure

- This document should show the relationship between the project team and the board IPC lead/s for the project.

Board IPC Governance Structure

- This may be part of an IPC policy or sit as a stand-alone document. It should show where the Infection Prevention and Control Committee (IPCC) or the equivalent within your board sits as part of the board's IPC governance arrangements, what groups it receives reports from (for example water and ventilation safety groups) and where it reports to (for example clinical governance committee).
- Evidence that the IPCC receives and reviews appropriate reports and updates relevant to each project and that IPCC minutes agendas and copies of any written reports relating to the project that have been submitted to that committee.
- Evidence that the HAI Executive Lead for the board is kept informed of any IPC issues, risks or improvement plans affecting the project or other healthcare premises nearby.
- Where the HAI Executive Lead chairs the IPCC, then the evidence that the IPCC is kept informed about the project will also be evidence of the HAI Executive Lead being kept informed. If the Committee is chaired by someone else, we will need details of the process by which the HAI Executive Lead is kept informed about the project and evidence that this has happened.

IPC resilience

Evidence that the board has mechanisms in place to ensure that IPC provision to the project is resilient.

- Provide details of the board's arrangements for ensuring that consistent IPC input to the project, over the full period of the project, will be available even when there are increased clinical demands on the IPC Team, for example during an outbreak or a situation like the recent COVID-19 pandemic.
- If board IPC resilience arrangements are limited (capacity or expertise) the risk should be captured on the project's risk register and details of the board's mitigation arrangements for this, for example arrangements for sourcing external expertise, and copies of the relevant entries in the risk register.

HAI-SCRIBE

Evidence that demonstrates an active formal process for initial completion and regular review and approval of the project's HAI-SCRIBE by a multidisciplinary team of key stakeholders, which includes:

- completed and approved HAI-SCRIBE documentation by all members of the project team which aligns to the current version of SHFN 30
- minutes and attendance (including roles) lists, of HAI-SCRIBE meetings
- an action tracker which monitors, and records completion of any actions identified during completion or review of the HAI-SCRIBE process and documentation
- HAI-SCRIBE evaluation should consider potential infection risks to patients and others both during construction and when the facility is put into use
- HAI SCRIBE should include both the new facility and any other healthcare facilities, buildings, and logistical arrangements that may be affected, wherever they are located

National Infection Prevention and Control Manual (NIPCM)

Evidence that the NIPCM is in use throughout the organisation and has been taken into consideration throughout the project. This could include:

- IPC Policies
- environmental audit programmes, including any additional practical examples of checks being during the project (for example increased environmental monitoring in facilities close to building work)
- an explicit note in the HAI-SCRIBE documentation that designs have been evaluated against the NIPCM (for example ensuring that there are adequate facilities for hand hygiene, patient placement, storage of PPE, and the safe management of equipment, laundry, and waste)

- a planned audit programme for newly commissioned clinical area(s), both before and after occupation
- IPCC specific notes and minutes relating to the NIPCM

Derogations

Evidence that IPC specialists have been engaged in all decisions regarding any derogations from guidance.

- A formal derogation approval process that explicitly includes IPC approval/ participation in a formal risk assessment(s) of any relevant derogations.

Evidence actions from previous KSARs have been completed

- Reports issued by NHSSA to the board at the end of each KSAR includes a set of 'detailed review findings' (DRFs) with recommendations for actions that that the Board should take in response to these previous findings.
- The board is expected to develop the DRFs into an action plan, completion of which will be reviewed as part of the next KSAR.
- The IPC lead/s should be familiar with all DRFs and be included as part of the board project team to develop the board action plan. The board should provide documented evidence that the actions identified have been completed or, if not completed, that progress that has been made towards completion.
- Any changes of processes implemented as a result of the DRFs or lessons learned from previous KSAR.

Additional information related to the Outline business case (OBC) KSAR:

Evidence that IPC specialists have been, and will continue to be, actively engaged in the procurement process.

- This applies to equipment, fixtures, and fittings and the procurement process for designers and other contractors.
- There is a formal process for reviewing designer and contractor bids that includes IPC specialists.
- This is expected to be included within the board's procurement strategy.
- Minutes of meetings which demonstrate that the experience of the companies bidding to work on the project was reviewed, and that IPC were present and engaged participants.
- Terms of Reference and minutes from procurement groups.

Evidence IPC specialists have been involved from the beginning of the project and will continue to be involved in the design process through to construction, commissioning and handover of the facility.

- Attendance lists from design briefing workshops.
- Minutes of meetings where the design was being actively reviewed which demonstrate that IPC were present and engaged. This may include meetings held as part of the NHS Scotland Design Assessment Process (NDAP).
- Records of site visits where IPC have been present.

Additional information related to the Full business case (FBC) KSAR:

Evidence that the designers and their teams have a proper understanding of infection prevention in relation to the project (this can sometimes be challenging to provide evidence of, so it is worth looking for that evidence well in advance of this review.

- Confirmation of relevant knowledge and experience should be provided to the board by companies tendering for the project and a review this evidence should be part of the procurement process.
- Details of training for infection prevention in the healthcare-built environment that contractors/sub-contractors have provided to their staff.

- Copies of contractors' CVs showing previous experience in healthcare projects and any associated training or education for infection prevention in the healthcare-built environment.
- Evidence of contractor learning from past health care projects.
- Any other documentation provided by contractors/sub-contractors to demonstrate that their staff have clear guidance on their roles and responsibilities in relation to IPC, for example Risk Assessment Method Statements (RAMS). Remember, these responsibilities extend both to patients who may be at risk due to proximity to construction work as well as patients who will be cared for in the new facility.

Evidence that ongoing planned preventative maintenance (PPM), cleaning and other services (for example catering and laundry) have been considered at this stage. This could include:

- assessment of PPM and cleaning requirements for the new facility and how these are to be met (beyond existing arrangements: If the plan is to simply flex existing services the board will need to provide evidence that existing services have sufficient capacity to accommodate the new facility)
- minutes of meetings where these arrangements are discussed with board estates and facilities staff
- instructions to designers
- proposed PPM and cleaning schedules

Additional information related to the Construction KSAR:

This review will be carried out once construction has begun and includes a site visit by the NHSSA KSAR team.

Evidence of the application of IPC and HAI SCRIBE (and ongoing review of) in practice for the project will provide assurance that IPC risks are being fully

considered during construction for the site underdevelopment and surrounding area(s).

- Documentation aligned to SHFN 30 which is completed and signed-off to development stage III by the key stakeholders.
- Minutes from meetings where HAI-SCRIBE arrangements are discussed, amended, and updated to evidence that HAI-SCRIBE documentation is regularly reviewed, with any issues identified being acted on.
- Schedules or meeting minutes demonstrating that IPC specialists have undertaken interim site inspections.
- Evidence of contractor and subcontractor competency and awareness of their roles and responsibilities with respect to IPC, for example induction training or toolbox talks.
- Evidence IPC risks are identified and managed, for example a HAI risk matrix and relevant risk register entries, actions from site inspections, minutes of water and ventilation safety groups, escalation processes and IPCC minutes.

Additional information related to the Commissioning KSAR:

This review will be carried out once commissioning has begun and includes a site visit by the NHSSA KSAR team.

- Evidence of IPC involvement in the development of the commissioning strategy/plan for the facility. For example, commissioning strategy and plan showing IPC involvement, minutes of commissioning meetings.
- Evidence of IPC roles and responsibilities during the commissioning phase and expected availability for the phase inclusive of expected validation reports to be reviewed/approved. For example, commissioning strategy and plan showing IPC involvement, minutes of commissioning meetings prior to and during commissioning phase.

- Evidence of IPC consultation/approval of any substantive changes to the design from previous review stage and that any changes have been subject to a change control process. For example, provision of change design processes and any changes, change process documentation and inclusion of IPC where applicable. Inclusion of minutes of change design meetings.
- Evidence of IPC involvement, agreement and approval of all derogations prior to the commencement of commissioning. Provision of derogation schedules, minutes of derogation meetings and any risk assessments associated with derogation.
- Evidence of IPC engagement regarding the patient cohort requirements for the facility. Documentation regarding clinical (including IPC) input to the project team review of proposed patient groups who will use the facility and how it is reflected in the commissioning brief. Have there been any changes to plans since the last KSAR? Does the proposed facility meet the initial project plan?
- Evidence IPC have been involved in selection of the commissioning company (independent company) who will undertake the commissioning process and that they have competency and training relevant to the healthcare built environment.
- Provision of commissioning planning and tendering meetings and commissioning strategy/plan.
- Evidence of IPC involvement with the procurement process and that all equipment, fixtures and fittings meet IPC standards and that the facility complies with the NIPCM. Minutes of equipping meetings showing IPC involvement and the equipping strategy/plan.
- Evidence that the proposed cleaning schedules for the facility are aligned to the National Cleaning Specification and that IPC have been involved in the planned cleaning of the facility from construction to clinical occupation.

Additional information related to the Handover KSAR

The handover stage is to confirm there is a good and comprehensive understanding of the category of patient who will use the proposed facility and that the project team consider how appropriate quality and safety standards will influence the build. It looks to provide assurance for the operational responsibility of the facility to be handed over to the health board.

- Evidence IPC involvement in the handover plan/process (for example, Exec board reports, Board minutes, IPCC, operational meetings etc) and expected availability for the process.
- Evidence IPC have reviewed all relevant final commissioning results and liaised with technical commissioning experts to consider any residual IPC risks (for example, minutes and actions from relevant technical and operational project groups such as IPCC, water and ventilation safety groups).
- Evidence that IPC have been involved in the sign-off of final water sampling testing results.
- Evidence all proposed cleaning schedules meet the requirements of the National Cleaning Specification and IPC involvement in the planning of these activities.
- Evidence of IPC involvement in the agreed processes for close out of observations or defects prior to handover. Minutes of close out meetings and completion of all agreed actions.
- Evidence that IPC have been involved in developing the proposed maintenance and operational processes for the facility (For example, development of cleaning schedules, ventilation and water testing requirements, audit programmes).
- Evidence that IPC resources are available to operationally support the facility once open. IPC work programme or IPC strategy noting the addition of the facility and resource available to support operationally. IPCC minutes where

resource for facility discussed. Papers to IPCC or board detailing IPC resource.

NHS National Services Scotland

NHS Scotland Assure Lessons Learned

Overview for the Interim Review Service – Ian Storrar

NHS Scotland Assure

Quality in the healthcare environment

A48891377

Table of Contents

Introduction

Health Facilities Scotland (HFS) and Antimicrobial Resistance and Healthcare Associated Infection (ARHAI) Scotland as part of National Services Scotland (NSS), have undertaken assurance audits and investigations into outbreaks of infections and operational issues in a number of significant healthcare construction projects. NSS reviewed healthcare buildings at different stages of their development, including those at detailed design, those where construction is almost complete and those in a live operational phase.

A number of common themes were found where lessons need to be learned across NHS Scotland and its construction supply chain to reduce the potential for a repeat divergence from guidance. This document will showcase topics where more consideration and effort is required (from project briefing, to project handovers and into the operational phase) and how these topics can be identified and discussed.

Areas noted for improvement are governance, auditing, stakeholder interaction, application of guidance and procedures before and after the facility becomes operational. Further refinements of this information will be developed for future release. This will target different participants in the life cycle of the healthcare facility with appropriate focus to allow them to fully understand their role and its impact on patient and staff wellbeing.

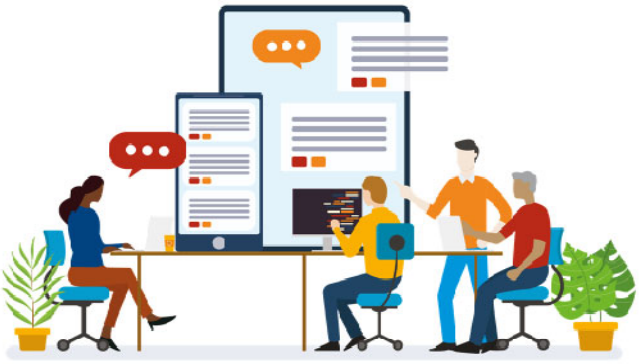
The headlines of the overarching recurring themes are outlined in this document. The discussions should be seen as a prompt to consider these factors as they relate to current projects.

The Interim Review Service was the precursor to the reviews being carried out by NHS Scotland Assure. The lessons learned from the Interim Review Service have been used to inform in the Key Stage Assurance Review Workbooks.

Roles and responsibilities

Clarity on roles and responsibilities is often an issue, especially for clinical teams whose contribution can be piecemeal. Late requests often result in significant design changes with associated risks. Lack of appreciation of the need for early decision making and guidance from clinical teams can also be a factor.

Early resolution of the roles and responsibilities would help to ensure that the stakeholders understood who was a part of each group and how to interact.



Brief development

The foundations of a successful project begins with establishing a clear brief which is understood and agreed by all stakeholders. A common theme which has contributed to problems is that important stakeholders are either not consulted or only involved at a particular stage. The engagement of stakeholders may be too late and result in decisions being postponed to a later stage (sometimes due to a failure to recognise the correct participants) or not taken at all.

From an engineering perspective, together with the Health Board Construction Requirements (BCR) another critical document is the health board's Environmental Matrix. This forms the basis of any Mechanical, Engineering and Plumbing (MEP) design and must be completed at the earliest possible date. It must have input from the full range of stakeholders and in particular reflect the clinicians' views of patients requirements and service on a room-by-room basis.

The starting point for the development of the matrix should be a record of the patient cohort and the forms of treatment for each space. This should also help to identify where these criteria need to be developed from the base principles (such as those shown in Scottish Healthcare Technical Memorandum (SHTM) 03-01 Part A: Appendices) or to suit the needs of specialist medical equipment.

It would:

- identify the degree of temperature control and air cleanliness which are appropriate
- determine the medical gas provision required
- select the risk to patient from electrical devices
- assist with the development of room air pressures or air flows in relation to risks to patients/staff/visitors and assess the required resilience

The activities in the room will also allow the designers to provide a suitable lighting scheme, assess the appropriate type of electrical installation and determine cooling requirements.

NHS Scotland Assure have a template for the Environmental Matrix which is available for health board use. This is a result of the Interim Review Service lessons learned activity.

It may prove necessary to amend the brief as the process develops and the impact of any changes can then be tracked against the original brief. The Environmental Matrix should at least include the criteria set out in the NHS Scotland Assure template or technical equivalent.

The brief should also set out the plans for how the building works might be phased. This has a large impact on the design and installation of the MEP installations. It may also outline the format in which record information must be delivered (and its minimum content) plus any provision for soft landings.

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Auditing of the design process

It is critical to audit the designs, particularly at key stage reviews. Health boards must have the correct team with sufficient, competent resource in place to look after their interests.

Where the health board doesn't have a Chartered Engineer to review the engineering proposals and an infection control specialist with knowledge of environmental impacts, they should look to procure those professional services. This process must have a robust method of recording findings and a mechanism to ensure that any item raised is closed out to the health board's satisfaction. Early consideration of Statutory Compliance Audit and Risk Tool (SCART) questions will help to ensure the design includes all elements needed to facilitate the processes covered in SCART.

Health boards may also wish to consider the NHS Scotland Assure Key Stage Assurance Review (KSAR) workbooks to assist in establishing the correct detail of design at particular gateways.
#

System compatibility

Once room environment requirements are agreed, it's essential the concept design for each room includes appropriate technology with sufficient capacity and control in order to produce the criteria. For example, a room which must be capable of being maintained at 18°C is unlikely to achieve this if no cooling is provided. **The form of control must reflect whether the temperature is to be allowed to float within a range or to be controlled to specific points within a range.** It should be possible to meet the environmental criteria at any time when the external air is between the winter and summer design conditions that have been agreed to suit the local conditions and resilience.

Sizing and control of the system must acknowledge the need to retain percentage relative humidity (% RH) in the room no higher than the maximum values recommended by the Scottish Health Technical Memorandum (SHTM) (or any other value, which is set and agreed as part of the health board's brief) or where specialist equipment and processes have specific requirements. The addition of moisture to the air (humidification) would only be considered in special circumstances.

Summer and winter external design conditions must be agreed and recorded in the environmental matrix.
The criteria should be agreed for:

1. the building load calculations
2. individual plant items (which may be different to point 1)

Design of the wholesome water systems must combat slow, infrequent or stagnant water flows, high cold-water temperatures or low hot water temperatures. An in depth risk assessment should be prepared of all of the measures that will be taken to limit adverse cold water temperature rise.

#
To avoid impacting on the existing service, it's necessary to understand the interaction with patient services and the existing hospital infrastructure.

For example:

- the full impact on the safety of the electrical network when new loads are added

- the ability of existing medical gas pipeline systems and plant to serve additional supplies
- the performance of standby electrical generators after new loads are introduced
- the impact on existing room air changes or pressure regimen

Resilience of all systems must be compatible with the service need. Plant, for example Uninterruptible Power Supply (UPS) units or air source heat pumps (ASHP), should be selected for all operating conditions to which they may be exposed. For example ASHP operating in very low external ambient temperatures, UPS operating on by-pass.

Risk assessments

SHTMs, Scottish Health Planning Note (SHPN), Health Building Note (HBN) and the National Infection Prevention Control Manual (NIPCM) indicate the minimum extent to which risk assessments are required.

The intention is to ensure that elements that affect infection control, resilience, safety, maintenance and the impact on the existing estate are fully considered. Similar to the brief, it's essential that all stakeholders are party to the assessments. It should be noted that there may be other risk assessments required by various legislation.

Understanding the existing infrastructure and patient service

It's necessary to understand the interaction with patient services and the existing hospital infrastructure to mitigate the impact on the existing service. Planning for patient pathways plus fire evacuation needs concentrated input from all stakeholders.

The knowledge of the existing building services infrastructure often needs to be supplemented with tests and in some cases, studies, due to missing record information. For example; the full impact on the safety of the electrical network when new loads are added, the ability of existing medical gas pipeline systems and plant to serve additional supplies, the performance of standby electrical generators after new loads are introduced and impact on existing room air changes or pressure regimen.

Detailed derogations process

It's important that the design begins with an in depth understanding of the extant guidance and not be limited to a review of reference tables within the guidance. As the design develops in conjunction with the stakeholders, it may be necessary to apply alternatives. In every occurrence, a derogation must be prepared.

All derogations must be subject to rigorous scrutiny by all stakeholders. They should include a fully developed argument as to why the change is necessary and an explanation as to how standards of patient care, safety, environmental control and energy conservation are as technically as good, if not better, than those achieved by compliance with guidance. Care

should be taken to ensure that terminology is clearly defined together with its context. An auditable record trail must be managed which clearly identifies that all stakeholders have understood and agreed with the derogation. The derogation process must be clear about which stakeholder has the authority to sign off on each derogation.

Derogations should not be a tool for 'value engineering' or cost reduction.

Detailed schematics of key systems

Schematics of the key MEP systems are essential to the successful development of the respective systems through design, installation, commissioning and operational stages of a project. They are a concise way of demonstrating the correct inter-relationship between components.

Schematics must be produced, as a minimum, for the following services. This is not an exhaustive list:

- water services plant
- water services networks
- ventilation plant
- ventilation systems networks
- above ground drainage
- heating plant
- heating networks
- cooling plant
- cooling networks
- HV Distribution
- LV Distribution
- UPS and Medical IT Distribution Systems
- earthing and bonding
- fire detection and alarms
- nurse call
- fuel supply systems
- fire suppression systems
- medical gas plant and manifolds

Space planning and service routing

Successful planning of the building layout will need to carefully include the provision for plant location and the routing of the services. It's also important to fully consider the ergonomic planning for spaces, including their associated medical equipment items.

The plant must be located where it can be easily accessed and safely maintained without creating disruption to clinical or patient services. Procedures that are contained in the Construction Design & Management (CDM) regulations should ensure that the finished product can be operated and maintained safely. The acoustic performance of the plant must also be considered to ensure no detrimental impact to the clinical or patient environment. Future access and replacement plans must also be clearly identified and form a part of the design.

The plant locations should also consider the suitability of routes from there to the point of use for the building service. Avoid arrangements which necessitate routing main building service routes through patient clinical spaces or which require access to components via a ceiling void or riser or from a patient room. Diverse routing and fire protection of essential building services must be factored in.

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Planning of building service risers should not only consider the route on plan of any building service in the riser, but also how all building services enter and exit it. Routing of wholesome cold-water pipework in separate risers will reduce the temperature rise of cold water.
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#
Minimising the heat gain to cold water systems must look at the entire installation where wholesome cold water pipes are kept away from hot water pipework, heat emitters, heat rejection equipment, high void temperatures and such like.

Inadequate planning of above ground drainage routes coupled with insufficient vertical drain stacks, can give rise to horizontal drains above clinical spaces, electrical or IT equipment or sensitive items. For example, ground floor drainage stacks, which are located to serve the ground floor sanitary ware, should not simply offset across and up through the building to pick up all drains in upper level rooms. The design should be planned such that access to clear blocked drains, in ceiling voids of sensitive spaces, should not be necessary. Drains should not dry out.

Consideration should also be given to the location and installation of fire and smoke dampers to ensure that they are fully accessible from both sides and can be installed in full compliance with the manufacturers certified installation details. Locations for medical IT systems and their associated EBBs, relative to the components that they serve, must be fully compliant with SHTM 06-01 and BS7671. #

Auditing of the contractor and their works

This process starts with selecting the contractor. It's essential to assess their competence for the size, complexity and programme for the work, as is their specific experience in the type and use of the building.

Reference should be made to Health and Safety Executive (HSE) guidance (leaflet - Using Contractors - INDG 368 (rev 1) published 06/12) and the emerging standards on competency from British Standards Institution (BSi); BSI Flex 8670.

Fully developed project specific Quality Assurance processes and

Quality Plans should form an integral part of the contractors' processes. These should incorporate all matters relating to sub-contractors including designers.

The health board should ensure that the contract includes the correct representation from the contractor to properly manage the works plus monitor and drive the specific healthcare needs of the project. The health board must also ensure that contractors have the correct skills, resource and time in the team that they assemble (to represent the interests of the health board) to audit the quality.

#

Contractor design packages (CDP)

The health board should ensure that contractor design packages (CDP) are suitably recorded within the contract and that the level of detail provided in relation to these is reflective of the project stage. CDP can have an impact on other services including power, cooling and ventilation. They can also have an impact on spatial co-ordination for plant and services distribution routes.

Often the CDP are based upon a performance specification and it's vital that it is suitably developed to allow not only cost certainty, but also to ensure that compliance with appropriate standards can be audited. The anticipated space planning and builders' work needs for the CDP must be considered during the early design process as part of the complete solution. Co-ordination with other disciplines must also be monitored.

The main MEP designer should be retained to review the CDP meets the design brief and the designer's intent (technically and spatially). CDP should be included in the BIM model.

Commissioning, demonstration and handover

Planning for commissioning should start during the design phase. As the design develops, a commissioning plan should be formed and recorded in parallel. Commissioning specialists, Authorising Engineers, Estates and Infection Prevention and Control must provide early, useful checks during the design. Designers must produce designers commissioning briefs in accordance with SHTM Guidance.

Programmes for pre-commissioning and for commissioning must not be shortened to falsely save time on a project time line or hurry handover. All test and commissioning results should be witnessed by the health board or their representatives.

The health board should consider the use of an independent commissioning manager to monitor and report on the process and its efficacy.

All record information must be made available in the format required by the contract before starting the client demonstrations. Record documentation that is given to the health board must include handover checklists, training records and SCART data that has been completed and signed off together with commissioning data.

Summary

These discussions are not exhaustive, but are intended to highlight areas where it has been evidenced that more rigour is required. While the comments are relatively brief, they are intended to add emphasis to the significant guidance that is available.

Some projects will benefit from an independent assurance audit in the future via NHS Scotland Assure. Others will not. It's critical that the due diligence applied by each health board can stand alone from an independent audit perhaps using the Key Stage Reviews as a reference point.

It's hoped the reader can recognise the footprint of the discussions above in the headings. They reflect elements of governance around specific areas where the healthcare built environment would benefit from applying greater rigour. Even in processes which are well established, such as HAISCRIBE and other interfaces with IPC, gaps exist in their implementation which should be managed.

The key to improvement is unlikely to lie in only targeting the most common deviations from guidance, but recognising that any of these points could cause a problem for patients and staff.

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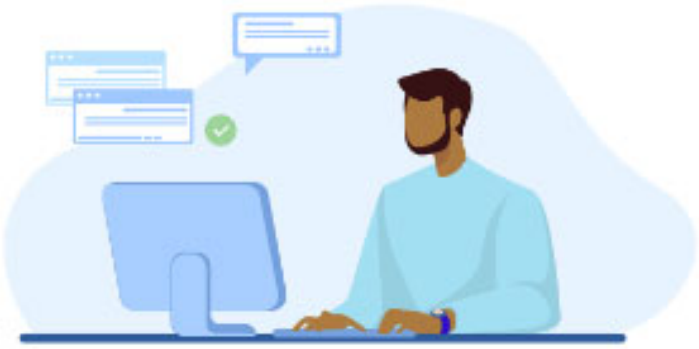

Examples of lessons learned

This section includes brief notes around problem issues. It is not an exhaustive explanation of each finding but aims to include enough detail to generate a future awareness of elements which should be considered by health boards and their advisors.

FIRE

- *absence of* combined fire and smoke dampers between corridors and patient sleeping accommodation
- self-closing devices missing from half leaf doors
- self-closing devices missing from doors between corridors (which access patient sleeping accommodation) and offices, stores (which are not kept locked)
- inadequate justification for omission of smoke detection in ceiling voids
- inadequate justification for omission of automatic detection from spaces such as toilets in accordance with BS5839
- absence of certification for fire curtains
- charging of electrical devices in corridors
- damaged fire seals at doors
- unprotected gaps in fire resisting materials

VENTILATION

- inadequate design air change rates
- inadequate/unclear room pressure differentials
- inadequate number of combined fire and smoke dampers
- filters incorrectly seated on frames in the AHUs
- isolation room ventilation not separated from the general system
- incorrect or unclear location for air pressure stabilisers (APS)
- inadequate separation between air intakes and discharges
- roof mounted AHUs without maintenance protection from the elements
- inadequate consideration of system performance creep associated with terminal HEPA filter fouling

ELECTRICAL

- unclear allocation of clinical risk categories (SHTM 06-01) and medical grouping (BS7671)
- excessive distance to Medical impedance terra earthed (IT) panels from outlets
- absence of or inappropriate siting of equipotential bonding busbars

- site fabricated equipotential bonding busbars not in compliance with BS7671 requirements.
- discrepancies or uncertainty around selectivity
- inadequate provision of fire protection of cables and busbars
- no local changeover for Medical IT
- incorrect completion certificates
- unexplained errors in test sheets
- conflicting information on documents

MEDICAL GAS SYSTEMS

- inappropriate location for safety valve
- inappropriate location of area valve service units (AVSUs)
- poor labelling and signage
- single point of failure on oxygen vacuum insulated evaporator (VIE) supply.
- difficult access to emergency isolation valve
- economiser difficulties
- missing/unclear derogations
- inadequate protection to oxygen incoming supply
- non-return valves missing
- inappropriate location of alarm panels

WATER

- abnormally high gram negative bacteria and TVC
- high cold-water temperature
- low hot water temperature
- type of expansion vessels either no flow or not clear
- lack of maintenance on taps
- assessment of bulk storage unclear
- filtration issues
- low carbon steel pipework used
- over sizing pipework
- insufficient valves
- dead legs in pipework

DRAINAGE

- use of air admittance valves (AAVs) in clinical areas with no evidence of hospital acquired infection (HAI) review or estates input regarding maintenance.
- lack of co-ordination of drainage pipework with other services, including stacks, falls and vents to atmosphere
- access to drainage manholes difficult and disruptive to “normal” operations
- lack of resilience in pumped systems

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NHS Estates Technical Bulletin (NETB 2023/01A): application of HEPA filter devices for air cleaning in healthcare spaces: guidance and standards

Publication (/publication)

Content

Applicability

This NETB applies to all healthcare spaces with ventilation requirements.

Objective

To provide additional technical guidance and standards on the use of HEPA filter devices for air cleaning in healthcare spaces.

Status

The document forms an addendum to Health Technical Memorandum 03-01 Specialised Ventilation for Healthcare Premises (HTM 03-01) (https://www.england.nhs.uk/publication/specialised-ventilation-for-healthcare-buildings).

Point of contact/feedback

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Executive summary

Ventilation* is an important line of defence for infection control in the healthcare environment. Its design and operation are described in Health Technical Memorandum (HTM-03-01) (https://www.england.nhs.uk/publication/specialised-ventilation-for-healthcare-buildings/). The current focus on ventilation has highlighted areas of high risk due to poorly performing and inadequate ventilation in hospitals and other healthcare settings. This may be due to change of room use, age, condition of air handling plant, lack of maintenance, challenges with effective use of natural ventilation or other. It is therefore important to bring these facilities up to the minimum specification of current standards, particularly recognising the challenges of COVID-19 and other infections.

Local HEPA filter-based air cleaners (also know as air scrubbers) are one option for improving and supplementing ventilation. The installation of a high efficiency particulate air (HEPA) filter air cleaner can reduce the risk of airborne transmission.

This guidance has been written as an interim specification to set the basic standard required for HEPA filter devices to be utilised in healthcare and patient-related settings. This edition is primarily aimed at portable and semi fixed (wall-mounted) devices. Devices relying on ultraviolet light (UVC) are the subject of a separate guidance document: Application of ultraviolet (UVC) devices for air cleaning in occupied healthcare spaces (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/).

* Ventilation is the process by which ‘fresh’ air (normally outdoor air) is intentionally provided to a space and stale air is removed. This may be achieved by mechanical systems using ducts and fans, or natural ventilation most commonly provided through opening windows. The local redistribution of air may also be construed as ventilation.

1. Introduction

Ventilation is an important feature in the control of airborne infection. However, the emergence of SARS-CoV-2 as a highly contagious virus has demanded new and innovative solutions to safeguard patients, staff and visitors. Health Technical Memorandum 03-01 Specialised Ventilation for Healthcare Premises (HTM-03-01) (https://www.england.nhs.uk/publication/specialised-ventilation-for-healthcare-buildings/) is a robust standard for ventilation of higher risk clinical spaces based on high air change rates using outdoor air to continually flush indoor spaces. The COVID-19 pandemic has shown that greater attention must be paid to the improvement and maintenance of ventilation in healthcare settings.

The focus on ventilation has also highlighted areas of high risk due to poorly performing and inadequate ventilation, particularly in older hospitals and other healthcare settings such as primary care and dental suites, which increase risks of nosocomial infections.

In cases, where current ventilation does not meet HTM-03-01 standards, this may be due to age, condition of air handling plant, lack of maintenance or other design or operational issues. In the case of naturally ventilated spaces, there is a reliance on staff or patients opening windows. Weather conditions, external noise and air pollution and restricted window openings for safety affect the ability to open windows and means that ventilation in some settings can fall below recommended rates.

Local HEPA filter air cleaners are one option for improving and supplementing ventilation. The correct installation and operation of a HEPA filter air cleaner can reduce the risk of airborne transmission.

Healthcare trusts are under pressure to improve ventilation and in the meantime are considering options including filter-based air cleaning. This standard will assist trusts in selecting and implementing good quality, reliable equipment.

There is substantial evidence from laboratory studies and real-world settings that filtration is an effective technology for reducing airborne pathogens within room air and HVAC systems. A number of research studies have been carried out which indicate that measured levels of microorganisms in air are greatly reduced by air filters [R1-R5, R7]. There is also evidence which directly associates use of

filter-based air cleaners with reductions in infection rates of environmentally-derived aspergillus [R8]. The potential of air scrubbers employing UVC or HEPA technology to mitigate SAR-CoV-2 risks is the subject of a rapid review (September 2022) [R.9]. Filter based air cleaners also remove other particulate matter and so can also reduce exposure to other air pollutants. However, air cleaners should not be used as a reason to reduce ventilation and care must be taken to ensure sufficient fresh air changes are provided for the dilution of medical gases and noxious odours, and the maintenance of appropriate oxygen and carbon dioxide levels to satisfy the Building Regulations Part F.

This document aims to serve as interim guidance and regulatory reference point for the design and correctly engineered deployment of HEPA filter devices in real-world settings with regard to effectivity and safety

It focuses on HEPA filter-based devices which can be positioned locally within a room; the document does not cover HEPA filters used within HVAC ducts. Local filter-based devices require fan assisted circulation to introduce the room air into the device, pass it through the filters and then to reintroduce the processed air into the room.

An important consideration regards the flow of the air which is induced, processed and distributed by the device external to the device itself. The design and placement of the device should promote efficient air distribution in the room space and avoid short-circuiting of air circulation relative to furniture, obstructions, and occupancy.

2. HEPA filter technology

HEPA filters comprise a porous structure of fibres or membrane which remove particles carried in an air stream. The mechanism by which particles are removed depends on the size of the particle. Larger particles are removed by impaction onto the filter while smaller particles <1 µm are removed through interception and diffusion. Interception occurs where the particle makes physical contact with the media fibres because particle inertia is not strong enough to enable the particle movement to continue. Diffusion is where random motion (Brownian motion) of the particle enables it to contact the media. These effects are enhanced by the electrostatic charges present on filters.

2.1 Selection of filters

Filter efficiency defines the fraction of particles removed and varies by size of particle. The most difficult size of particles to remove, known as the most penetrating particle size (MPPS), for the majority of filters is around 0.3 µm;

particles larger or smaller than this size are captured more effectively. For healthcare applications it is recommended that devices should contain filters classified as High Efficiency Particulate Air Filters (HEPA) under BS EN 1822-1 (https://www.iso.org/obp/ui/#iso:std:iso:29463:-1:ed-2:v1:en) or ISO 29463-1 (https://www.iso.org/standard/67816.html). HEPA filters have a filter efficiency of at least 99.95% (H13 filter) or 99.995% (H14 filter) for the MPPS, however the performance in situ is sometimes lower depending on the filter and device design and the air flow rate (section 5.1 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#5-engineering-design-specification-and-performance-validation)).

Microorganisms range in size from around 0.1 µm for the smallest viruses to several µm in diameter for larger bacteria and fungi. Some fungi and bacteria may be dispersed independent of other material, however, many pathogens will be released on or within another material and therefore the size of the particle that needs to be captured is larger than the pathogen itself. For example, respiratory and gastroenterology viruses will be released within liquid media that contains proteins, salts, surfactants, etc and evaporates to form particles that are larger than the virus itself. Similarly, many skin associated bacteria are released on skin squame which are larger than the bacteria.

Some filter-based air cleaning devices contain lower grades of filter. These devices may be appropriate in non-clinical areas, but as the filters have a lower performance for particles relevant to the size of airborne pathogens they are not recommended in settings with vulnerable patients.

It is common for HEPA filter-based devices to incorporate a coarse grade of filter (typically ISO ePM10 >50% under ISO 16890-1 (https://www.iso.org/standard/57864.html)) to act as a dust filter. Some also include a carbon filter to manage odours and volatile organic compounds. Some devices contain several separate filters, while others incorporate the different stage filters into a single cartridge type unit.

2.2 Inclusion of other technologies

Devices which include germicidal ultraviolet (UVC) light alongside HEPA filters are likely to be effective [R4]. Where these devices are considered, this standard takes precedence in terms of clean air performance if the UVC lamp is located after the HEPA filter (i.e. the HEPA filter is the primary device for microbial removal). However, all the safety requirements pertaining to the UVC within that standard should also be complied with.

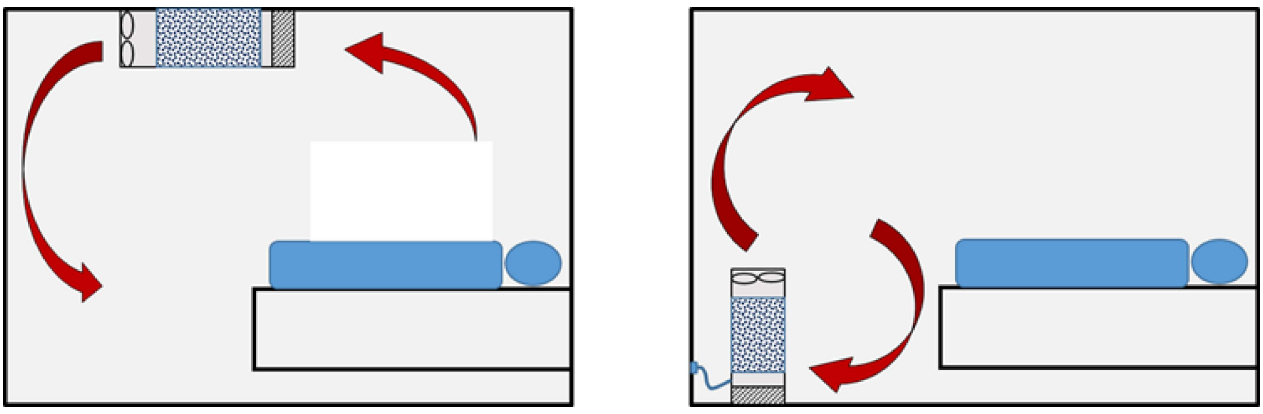
Devices which incorporate ionisation, photocatalytic oxidation, electrostatic precipitation or other similar technologies alongside filters are not currently recommended for healthcare use unless there is clear evidence for both effectiveness and safety. These devices can sometimes introduce, or create through secondary reactions, chemical by-products into a room which may themselves have an adverse health effect [R4, R11]. The independent research evidence that these products are any more effective at safely reducing microbial loads in air is still emerging.

3. Applications and sizing

Standalone, floor mounted devices can be positioned at any suitable location in a room. These devices are plugged into a standard electrical socket so do not require any installation, although location is important as detailed in sections 8.2 and 8.3.

Fixed devices are semi-permanently mounted to a wall or ceiling. These devices will normally be permanently wired into the room electrical systems rather than plugged into a wall socket. Some manufacturers offer local systems that can be interfaced with the ventilation system and are able to offer pressure differential control in a room.

Figure 1: Representation of typical air flows with respect to a recumbent patient in a regular room for two filter device locations: fixed, wall- or ceiling-mounted **(left); mobile, floor-standing (right)**



(https://www.england.nhs.uk/wp-content/uploads/2023/05/typical-air-flows.png)

In rooms without natural or mechanical ventilation, or where the ventilation falls short of statutory requirements or regulatory advice, auxiliary devices may be deployed to enhance the equivalent air changes.

The installation of HEPA filter-based air cleaners can be considered to contribute additional ‘equivalent’ air changes (eACH). For example, a treatment room with 6 ACH could achieve the equivalent of 10 ACH by installing a local filtration unit

which recirculated and cleaned the equivalent of 4 eACH. Hence, to meet the requirements that comply with HTM-03-01, the number of devices required will be dictated by the existing background levels of ventilation.

The high filter efficiency of HEPA filters means that the single pass efficiency of an air cleaning device for the MPPS should result in at least a 99% (2 log) reduction in the concentration of particles, including microorganisms, that pass through the device when in normal operation. However, the performance within a room depends on both the flow rate through the device and how it distributes the air in a room.

The performance of filter-based devices is described by some manufacturers in terms of a Clean Air Delivery Rate (CADR) which is usually expressed in metres cubed per hour (m^3h^{-1}) (some devices quote the CADR in cubic feet per minute, cfm). Where a CADR is given it should be derived from measurements of how well the device removes a defined size of particles in a test room environment; CADR is usually measured using particles rather than microorganisms. CADR is a function of the airflow rate through the device, the quality of the filter and the way the device distributes air in the test room.

Other manufacturers adopt different metrics such as the time to reduce particle concentrations in a room by a specific percentage.

The CADR or other metrics can be used, with care, for design purposes as they express how the device will perform in a standardised test room. However, it is important to note that the actual performance will depend on the particular location and operation of the device, including the room size, layout, background ventilation, device design and maintenance (section 8 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#8-maintenance)).

It is not recommended to use an air cleaning device with a lower grade of filter even if the quoted CADR is high, as the device may be less effective against the smallest pathogen carrying particles.

The CADR used for design purposes should be the rate applicable to the device setting at which the device is most likely to be operated and where the noise level is during operation is at a level of ≤50 dB measured at 3 m (dB_{3m}) (section 5.3 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#5-engineering-design-specification-and-performance-validation)).

4. Engineering implementation

4.1 Regulatory and standards compliance

If selecting a device that incorporates both UVC and HEPA filters the device should also comply with Application of ultraviolet (UVC) devices for air cleaning in occupied healthcare spaces (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/).

Standards are an integral part of product design and development and are important in medical applications. The Low Voltage Designated Standards (about:blank) should be followed implicitly as a minimum.

IEC 60601 is a series of technical standards which apply to medical electrical equipment and medical electrical systems for basic safety and essential performance. The basic scope of IEC 60601 is the safety of patients and users. It is recommended that the design of standalone HEPA filter devices should follow the principles of the 60601 Standard to ensure risks to patient and user safety within a medical environment are recognised and mitigated (section 4.1.2 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#4-engineering-implementation)).

4.1.1 CE and UKCA marking

CE and UKCA marking are standards that appear on products traded on the extended single market in the European and UK economic areas. The marking signifies that the product has been assessed to meet high health, safety, and environmental requirements.

- Selling products in Europe:
  - use of the CE-mark declares that the product meets the legal requirements for sale throughout the European Union. Note: note that some products are marked China Export (CE) which should not be confused with the EU standard.
- Selling products in the UK:
  - the UKCA-mark is the product marking used for products being placed on the market in Great Britain (England, Scotland, and Wales)
  - the UKCA-mark applies to most products previously subject to the CE-marking. The technical requirements (sometimes referred to as ‘essential requirements’) must be met.

4.1.2 Electrical safety

- Compliance with the Low Voltage Directive is mandated implicitly.
- Compliance with the IEC 60601standard is recommended.
- Class I (exposed metal components connected to earth):
  - protective earth continuity <0.2 MΩ
  - insulation tests: ≥50 MΩ
  - earth leakage: ≤5 mA in normal condition (NC), ≤10 mA in SFC (single fault condition)
  - enclosure leakage current: ≤1 mA in NC, ≤0.5 mA in SFC.
- Class II (double-insulated enclosure):
  - insulation tests: ≥50 MΩ
  - enclosure leakage current: ≤0.1 mA in NC, ≤0.5 mA in SFC.

Class III devices are not recommended.

4.1.3 Electrical wiring

Electrical wiring should be in accordance with IET Regulations BS 7671:2018 Requirements for Electrical Installations (about:blank).

4.2 Ozone and other emissions

Devices which operate using filters only do not produce ozone or other chemical emissions. Devices which incorporate other technology alongside filters are not recommended, however, if they are used manufacturers are required to provide assurance that devices do not produce ozone levels or other chemical pollutants in excess of the Workplace Exposure Limits (UK Workplace Exposure Limit (WEL) for ozone of 0.2 ppm (15 minute reference period)).

5. Engineering design, specification and performance validation

5.1 Device verification

As the performance of a HEPA filter is determined by the size of particles rather than the species of microorganism, it is not necessary for a manufacturer to conduct validation tests using microorganisms. Performance and validation tests carried out by manufacturers can be carried out using inert particles of an appropriate size, usually in the 0.5–2 µm size range. -0

Manufacturers should provide evidence that the HEPA filter used within the device meets BS EN 1822-1/ISO 29463-1 or an equivalent standard, and that the air cleaning device with filters in situ has been tested to an appropriate protocol that demonstrates how the device is likely to perform in a typical healthcare setting. Performance data including airflow rate through the device, filter pressure

drop and measured impact of the device on particle concentration in a suitable test environment should be provided for each operational fan speed and for the MPPS.

Device verification, as defined by the manufacturer, should be carried out on first installation to ensure filters are correctly installed and at every filter change. If filters are not correctly installed in devices, leakage around the edge of the filter can result in significant underperformance of the device. A verification check to ensure the device is operating correctly is also recommended if a device is moved to a different location within a hospital.

The verification test is designed to provide assurance that there is no unfiltered air bypassing the filter. This should be carried out by visual inspection to ensure the filter is intact and correctly seated, followed by appropriate measurement, usually through the pressure drop across the clean filter. Manufacturers should either provide a mechanism by which this is carried out in an automated way or by providing ports for a manual pressure drop measurement. Data on the expected pressure drop across the filters at each device flow rate should be provided and should be measured automatically within the device or manually by a qualified person at filter change. Where devices incorporate automated processes for measurement and calibration, manufacturers should provide evidence that this is robust and has been verified in a laboratory setting.

5.2 Filter life

Devices should be optimised to minimise filter replacement times and allow for a straight-forward replacement schedule. A pre filter typically of grade ISO ePM10>50% should be installed within the unit to maximise the life of the HEPA filter

In most healthcare environments devices should be selected such that filters should last around 12 months. Some may last longer than this, however, in environments which are more contaminated or at higher humidity filters may need replacing more frequently.

Devices should incorporate a dirty filter warning indicator or alarm for both the pre filter and the HEPA filter, to provide an easy visual indication to healthcare staff when a filter requires changing or when any other device maintenance is required. This should be in addition to the ability to measure the filter pressure drop for verification (section 5.1 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#5-engineering-design-specification-and-performance-validation)).

5.3 Noise considerations

Devices in occupied areas should normally operate at a sound level of ≤50 dB measured at 3 m (dB_{3m}). Exceptionally, for operation at boost such that might be used to purge a room higher sound levels may be acceptable; this should be assessed based on the use of the room.

Noise is a particular consideration when devices are used in rooms where patients are sleeping, and lower sound levels than stated here may be required depending on local environmental conditions. Further guidance on wider considerations around acoustics in healthcare is given in HTM-08-01 (about:blank).

6. Competent persons

In the present context, competent persons (it should be noted that competent person may be defined differently in other documents, including in HTM03-01) are recognised as individuals who are suitably qualified and experienced with professional expertise in one or more of the following areas in the healthcare setting: the design and specification of HEPA filter-based systems (including with airflow assessment), the technical maintenance of HEPA filter devices and systems, and the implementation of schemes employing HEPA filter devices.

Competent persons should have training and familiarity with the HEPA filter-based devices used within the particular healthcare setting to be able to size, specify, operate and maintain devices effectively.

Further, involvement of appropriate people with particular expertise in infection prevention and control are essential during the process of specifying and deploying devices.

7. Engineering and operational considerations

7.1 Hazard, risk and operational delivery

A ventilation design incorporating HEPA filter-based air cleaners will require a hazard and operational study (HAZOP). This process will be convened by the local Ventilation Safety Group (VSG) (a group of individuals with recognised expertise in the design and operation of ventilation devices and systems responsible for the governance of the device deployments, as defined in HTM 03-01) which will include competent persons (section 6 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#6-competent-persons))

including the Authorising Engineer (Ventilation) and representation from infection and prevention control, nursing and clinical engineering and/or estate management departments. The process will require considering infection control and health and safety aspects specific to the clinical requirements and patient groups within the particular setting and the safe installation of a portable electrical device.

7.2 Ventilation and device effectiveness

The Ventilation Safety Group will consider air flow strategies which achieve the most effective ventilation of occupied spaces. This requires that all factors such as air flow rate, mixing and distribution, dilution, thermal buoyancy and the impact of occupant movements and must be considered.

Airflow patterns and ventilation rates can be evaluated using measurements of air velocities, indoor air quality (IAQ) monitoring and visual methods such as smoke tracing. Computational Fluid Dynamics (CFD) modelling can also be a useful tool to assist the ventilation design engineer to assess airflow patterns in the rooms where HEPA filter devices are to be located. CFD, particle tracing and other forms of airflow assessment can be used to identify the optimal locations to place devices. CFD modelling requires specialist knowledge, and any simulations should be carried out by a competent person.

Airflow and particle/IAQ measurement, visualisation and CFD simulations can illustrate typical airflow patterns but unless carried out over a sustained period of time may not be able to capture all of the fluctuations that occur in real environments, particularly those that are naturally ventilated.

Air cleaner device performance depends on both the flow rate through the HEPA filter and the way the device distributes the air in a room, and both are important factors for ensuring devices are effective and properly positioned. Assessing how a device affects the air flow in a room using the approaches described above can give greater assurance that the device is sufficiently sized for the room and is positioned to be able to distribute air properly.

Although many devices are supplied as portable, they should be sized to the space where they are normally used. If a device is moved to a new location then it is recommended that a suitable risk assessment is undertaken by a competent person to ensure that the device is still likely to be effective.

7.3 Installation

The installation of any HEPA filter-based devices should comply with all building regulations and electrical guidance. A risk assessment should be undertaken by competent persons (section 6 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#6-competent-persons)) including representation from infection and prevention control, nursing and clinical engineering and/or estates departments.

Units should be positioned so that they do not interfere with the provision of care or provide an obstruction. Floor standing devices can be a trip hazard in some locations and need to be positioned to ensure they or their cables do not pose a risk to patients and staff and do not impede access. This includes ensuring that power cables or other elements of the device do not pose a ligature risk. Consideration should include risks for people who have visual impairments or restrictions on their mobility.

Devices should consider the manufacturer's recommendations around the best positioning to maximise the effectiveness alongside practical considerations around space available in a room and access to power supply, cable routes, etc.

Devices should ideally be positioned so that there is effective airflow into and out of the unit. Airflow inlet and exhaust panels on devices should not be blocked by furnishings and devices should be designed such that objects cannot be placed on top to cover the vents. Patient comfort should also be considered with devices positioned such that they do not create uncomfortable draughts.

Consideration should also be given to whether portable devices could be deliberately or accidentally moved or pushed over by patients or visitors. Device design should be stable and not easily toppled. In some settings it may be prudent to ensure there are design features that enable devices to be secured so that they cannot be moved. Devices which rely solely on remote controls or app-based controls are not recommended for healthcare settings. Remote controls tend to get lost and there may be privacy or Wi-Fi connectivity issues with app-based control. Devices which use voice activated controls linked to the internet (eg Alexa type systems) should not be used in healthcare settings as there are likely to be concerns around privacy.

7.4 Commissioning

Commissioning shall involve 'acceptance testing' according to local SOPs and include electrical safety testing to IEC 60601 (section 4.1.2 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#4-engineering-

implementation)). An audit of document compliance to the Low Voltage Directive (about:blank) is to be recorded. Where medical device classification is claimed, regulatory compliance with ISO 13485 Class 1 should be evidenced.

7.5 Verification and validation of performance

Manufacturers should evidence claims of engineering specifications (verification) and efficacy (validation) (section 5.1 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#5-engineering-design-specification-and-performance-validation)).

Devices should be checked every time the filter is changed (section 8.2 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#8-maintenance)) or the device is moved and periodically to ensure that performance is maintained. This can be accomplished by automated or manual measurement of the filter pressure drop under all of the device flow rate conditions as detailed in (section 5.1 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#5-engineering-design-specification-and-performance-validation)).

7.6 Training

Clinical and nursing staff in areas where HEPA filter-based air cleaning devices are located should receive training on operational and safety issues. A protocol should be in place such that staff can notify clinical engineering and/or estates management departments of suspected device malfunction. In a healthcare context, such training can often be manufacturer or supplier provided and might be included in staff mandatory training programmes.

7.7 Labelling

All HEPA filter devices should be labelled to inform users of operating procedures and potential hazards. Labels should serve to make users aware of how to interact with HEPA filter devices.

8. Maintenance

Day-to-day cleaning of devices and routine visual inspection (eg damage to casing, wear on cables, etc) can be carried out by healthcare or cleaning staff. Maintenance including filter replacement should only be conducted only by a designated competent person.

8.1 Cleaning

The outside surfaces of devices should be designed to be easily cleaned as part of standard cleaning regimes in the healthcare setting and should not have features which are prone to collecting dust and dirt. The device should be robust to cleaning materials routinely used in healthcare settings. Cleaning instructions should be provided by the manufacturer and easily visible to staff attending the unit.

8.2 Filter replacement

SOPs must be in place for both replacing and safe disposal of used filters. Evidence suggests that the hazards posed by filters are small (Mittal, 2011 (http://doi.org/10.1177/153567601101600305)), but there could be potential risks from pathogens that have been trapped by the filter and hence risk assessments and guidance should be in place.

Filter changes should follow the manufacturer guidance regarding the process and internal cleaning of the device. Filters should not be changed in clinical areas due to the possible hazards of microorganism and dust dispersal during the procedure. Those carrying out filter changes should wear appropriate PPE as agreed with their infection control team.

Disposal of used filters requires a suitable risk assessment for safe bagging, handling and appropriate waste disposal for the used filter as it is potentially contaminated with pathogenic microorganisms.

When new filters are installed they must be correctly seated as per manufacturer guidance to ensure there are no airflow leaks around the filter. Verification tests should be carried out after the new filter is installed (section 5.1 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#5-engineering-design-specification-and-performance-validation)).

8.3 Annual checks

All devices should undergo at least annual checks to verify their continuing performance. These checks should include, but are not limited to, the following:

- visual inspection of external and internal
- electrical safety test (section 4.1.2 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#4-engineering-implementation))
- check alarms simulate failures

- check filter run times and replace if necessary (section 8.2 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#8-maintenance))
- clean internals of the device.
- replacement and safe disposal of any filters (section 8.2 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#8-maintenance))
- check and document air flow rate measurements at different fan speeds against manufacturer's characteristic-specification (section 5.1 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#5-engineering-design-specification-and-performance-validation))
- check and document noise levels against manufacturer's characteristic-specification (section 5.3 (https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/#5-engineering-design-specification-and-performance-validation))
- for devices that also include UVC, ensure checks set out in Application of ultraviolet (UVC) devices for air cleaning in occupied healthcare spaces: guidance and standards (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/), have also been completed
- apply annual check sticker.

9. Building Management System (BMS) module

The incorporation of a BMS (Building Management System) module into HEPA filter devices is recommended to afford the assurance of effective operation and to support maintenance scheduling. This can also be used to help identify any devices which have been inadvertently switched off, as well as the physical location of devices that are portable. Modules should be enabled with the Modbus or BACNet* open protocol for interfacing with existing an BMS.

*BACnet is a communication protocol for building automation and control (BAC) networks using the ASHRAE, ANSI and ISO 16484-5 standards protocol.

Annex 1 – Bibliography

Laboratory chamber studies demonstrating effectiveness of HEPA filter devices against particles and microorganisms

- [R1] Miller-Leiden S, Lohascio C, Nazaroff WW, Macher JM (1996) Effectiveness of in-room air filtration and dilution ventilation for tuberculosis infection control. Journal of the Air & Waste Management Association 46: 869–882. doi:10.1080/10473289.1996.10467523 (https://doi.org/10.1080/10473289.1996.10467523)
- [R2] Offermann FJ. et al (1985) Control of respirable particles in indoor air with portable air cleaners. Atmospheric Environment 19: 1761–1771. doi:10.1016/0004-6981(85)90003-4 (https://doi.org/10.1016/0004-6981(85)90003-4)
- [R3] Ueki H, Ujie M, Komori Y, Kato T, Imai M, Kawaoka Y (2022) Effectiveness of HEPA filters at removing infectious SARS-CoV-2 from the air. mSphere 7(4):e0008622. doi:10.1128/msphere.00086-22. (https://doi.org/10.1128/msphere.00086-22)
- [R4] Beswick A, Brookes J, Rosa I et al. 2022. Room based assessment of mobile air cleaning devices using a bioaerosol challenge. Applied Biosafety Journal. Published online Dec 2022. doi:10.1089/apb.2022.0028 (https://doi.org/10.1089/apb.2022.0028)
- [R5] Lindsley WG et al (2021) Efficacy of portable air cleaners and masking for reducing indoor exposure to simulated exhaled SARS-CoV-2 Aerosols — United States, 2021. Morbidity and Mortality Weekly Report (MMWR) 70: 972–976. doi:10.15585/mmwr.mm7027e1 (http://dx.doi.org/10.15585/mmwr.mm7027e1)

Testing approach for Clean Air Delivery Rate

- [R6] Foarde KK, Myers EA, Hanley JT, Ensor DS, Roessler PF (1999) Methodology to perform clean air delivery rate type determinations with microbiological aerosols. Aerosol Science and Technology 30: 235–245. doi:10.1080/713834074 (https://doi.org/10.1080/713834074)

Application of HEPA devices in healthcare setttings

- [R7] Conway Morris A, Sharrocks K, Bousfield R, et al, The Removal of Airborne Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) and Other Microbial Bioaerosols by Air Filtration on Coronavirus Disease 2019 (COVID-19) Surge Units, *Clinical Infectious Diseases*, Volume 75, Issue 1, 1 July 2022, Pages e97–e101, doi:10.1093/cid/ciab933 (https://doi.org/10.1093/cid/ciab933)
- [R8] Abdul Salam ZH, Karlin RB, Ling ML, Yang KS. The impact of portable high-efficiency particulate air filters on the incidence of invasive aspergillosis in a large acute tertiary-care hospital. *American Journal of Infection Control*.

2010 May;38(4):e1-7. doi:10.1016/j.ajic.2009.09.014 (https://doi.org/10.1016/j.ajic.2009.09.014).
- [R9] Bowles C, et al. A rapid review of supplementary air filtration systems in health service settings. September 2022. doi:10.1101/2022.10.25.22281493 (https://doi.org/10.1101/2022.10.25.22281493) medrxiv preprint

Wider reading on air cleaning applications

- [R10] Medical Advisory Secretariat. Air cleaning technologies: an evidence-based analysis. Ontario health technology assessment series vol. 5 (2005) https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3382390/ (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3382390/)
- [R11] SAGE-EMG: Potential application of air cleaning devices and personal decontamination to manage transmission of COVID-19, 4 November 2020 https://www.gov.uk/government/publications/emg-potential-application-of-air-cleaning-devices-and-personal-decontamination-to-manage-transmission-of-covid-19-4-november-2020 (about:blank)

Annex 2 – Acknowledgements

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Annex 3 – Glossary

- **Active operational life:** A product's operational life is the period for which a product is in use before it becomes obsolete, in terms of UVC lamps it is typically 70% of original efficacy.
- **Air changes per hour:** Air changes per hour (ACH) is the measurement at which air volume per hour is added to a room divided by the total volume of the room. It represents the number of complete air exchanges in one hour under perfect air circulation conditions. See also Equivalent air changes per hour.
- **Air circulation:** Mixing of the air from natural or mechanical ventilation sources inside an enclosure.
- **Air circulation efficiency (%):** A measure of the effectiveness of air circulation in a real enclosure with obstructions such as occupancy and furniture, compared with perfect mixing as quantified by ACH/eACH. CFD studies in hospital and high-street treatment rooms indicate that the air circulation efficiency can vary between 40% and 80% depending on the device placement and proximity of furniture, equipment and occupancy. Similar variance applies to AGP-clearance and therefore will affect fallow time.
- **BMS (Building Management System):** A computer-based control system installed in buildings that controls and monitors the building's mechanical and electrical equipment such as ventilation, lighting, power systems, fire systems and security systems.
- **Building regulations:** Building regulations set standards for the design and construction of buildings to ensure the safety and health for people in or about those buildings. They also include requirements to ensure that fuel and power is conserved, and facilities are provided for people, including those with disabilities, to access and move around inside buildings. Current standards require that Health Care buildings conform to NHS standards. For ventilation NHS HTM-03 applies.
- **CFD (computational fluid dynamics):** Computer-based fluid dynamics modelling providing a means to simulate air flow combined with

convective/buoyant/conductive/radiative heat transfer, particulate transport (aerosols and droplets) and turbulence.

- **Characteristic specification (Characteristic verification):** A measurable property of the device that can employed routinely by the user to provide assurance of device operation to the verification model. See Verification.
- **Clean Air Delivery Rate (CADR):** Experimentally derived data that expresses the performance of a filter-based air cleaning device in a test room. CADR is a function of the airflow rate through the device, the quality of the filter and the way the device distributes air in the test room.
- **Clearance:** The relative removal of a contaminant usually expressed as %. See Log reduction.
- **Decontamination:** Decontamination describes the reduction of pathogenic microorganisms to a safe level for human use. Technically, this means reduction by a minimum of 1 log step, meaning 90%.
- **Disinfection:** The term disinfection is not clearly defined in a technical sense. Generally, for the purposes of this standard, it means a reduction of pathogenic microorganisms by a minimum of 3 log steps Or 99.9%
- **Equivalent air changes per hour, eACH:** Equivalent air changes per hour, or eACH, is a measure of the 'equivalent' amount of air that is cleaned by a HEPA or UVC device as a ventilation rate of new outside-air changes would achieve in one hour. See ACH. Note that this applies to decontamination and does not obviate the need for meeting minimum fresh air standards.
- **Electrical Safety Test (EST):** Requirement of the Low Voltage Directive to demonstrate general electrical safety.
- **Electrostatic precipitation (ESP):** A method of removing particles from air by applying a charge to the particles (often through an ioniser) and then capturing onto a plate which has an opposite charge. Some filter-based air cleaners incorporate ESP.
- **Fallow time:** Time (s/min/hr) allocated to a treatment room without occupancy to allow for clearance of the room after a contamination event (eg an AGP) to recover safe levels for occupancy.
- **Germicidal ultraviolet/germicidal ultraviolet irradiation:** Referred to commonly as GUV and UVC. Both are one and the same in that they refer to ultraviolet C spectrum light that is germicidal.
- **Hazard assessment:** A hazard assessment is a thorough check of the occupational environment. The purpose of a hazard assessment is to identify potential risks and hazards in the area, as well as to identify appropriate safety measures to be used to mitigate, eliminate or control the identified hazards.
- **HAZOP:** [Hazard Analysis and Operational study] – a systematic way to identify hazards in a work process.
- **HEPA:** High Efficiency Particle Air Filter, used to describe a filter with a very high particle filtration efficiency with over 99.95% removal for the smallest

particles (see MPPS).

- **IAQ (Indoor Air Quality):** A generic term used for air quality in enclosed spaces, usually referring to the combination of harmful gases (eg. CO2 and CO levels measured in parts-per-million, ppm), temperature (for thermal comfort), total volatile organic content (TVOCs measured in parts-per-billion, ppb), relative humidity (%) and particulate matter size (respiratory irritants/hazards) measured in micrograms/m3, eg. PM2.5, PM10.
- **Infection:** The process by which pathogens penetrate the body of an organism and multiply therein. Depending on the transmission route, we distinguish between contact infections and airborne infections.
- **Infectiousness:** Measure for describing the ability of a pathogen to cause actual infection in a host after transmission occurs.
- **Ioniser:** A device that uses a high voltage to electrically charge air molecules and particles in air. Ionisers are sometimes used as part of electrostatic precipitators or are used to emit ions into a room. There is evidence that ionisation of air can result in ozone generation.
- **Ionising radiation:** Ionising describes the type of radiation capable of permanently removing electrons from atoms or molecules. Note: UVC radiation has no ionising power.
- **Log reduction:** The reduction of a contaminant can be quantified in log stages. A Log reduction of ‘x number’ therefore means a reduction by ‘x number Log’ stages starting from a given population. The reduction by 1 log stage means a reduction of 90%, since only 10% have survived from the original population. See Clearance.
- **Log stage (a.k.a. Log step):** A log stage or log step describes the reductio n of a population by a (further) power of ten: in other words, 1 log stage = 90%, 2 log stages = 99%, 3 log stages = 99.9%, etc. See Log reduction.
- **Microorganism (microbe):** A microorganism is an organic structure so small that they can generally only be seen with the aid of a microscope and include viruses, bacteria and fungi. Such structures are usually single-celled, although they are occasionally multi-celled.
- **MPPS:** Most Penetrating Particle Size. The size of particle that leads to the lowest performance for a filter. For HEPA filters this is typically in the region 0.2-0.5 µm diameter particles.
- **Nosocomial infection:** An infection contracted in a hospital or care institution.
- **Ozone:** Represented as O3. Ozone is a gas with strong oxidation properties that is toxic in low concentrations. Ozone can result from the oxidation of O2 irradiated by far UVC.
- **Pathogen:** Pathogens are microorganisms capable of causing disease or illness in living creatures.
- **Photocatalytic oxidation (PCO):** Use of ultraviolet light with a catalyst (usually titanium dioxide) to generate hydroxyl radicals. These can

potentially react with air pollutants to break them down, however they may also produce ozone or act to convert some pollutants into other chemicals.

- **Sanitisation:** The process of reducing microbiological contamination. See Clearance and log reduction.
- **Single pass effectiveness:** The percentage (or log) reduction in particles or microorganisms in the air that directly passes once through an air cleaning device. This is determined by the grade of the filter and the air flow rate through the device.
- **SOP:** (Standard operating procedure) A set of step-by-step instructions compiled by an organization to help workers carry out routine operations.
- **Sound pressure level: dB3m:** The acoustic output pressure represented by dB measured at 3 m from the source.
- **Validation (bio-validation):** The process to provide assurance that the device is effective as claimed by the manufacturer. For the purposes of this standard, assurance that particle removal or microorganism reduction is achieved as claimed.
- **Verification:** The process to provide assurance that the device performs to the manufacturer's specification. For the purposes of this standard, assurance that air flow and filter performance are as claimed.
- **Viruses:** Viruses are particles or information carriers dependent for survival and replication upon the metabolism of a host cell since they themselves have no cytoplasm and are incapable of metabolism. Viruses are thus, de facto, not living organisms.

The National Estates and Facilities team at NHS England is responsible for producing Standards and Guidance for the NHS estate and ensuring that the information and guidance they contain remains up-to-date and relevant for users.

NHS Estates Technical Bulletins (NETBs) enable updated guidance to be passed to local systems, ensuring we maintain our focus on patient safety. NETBs contain technical guidance and standards which systems and organisations are required to consider and implement, where applicable. Boards are responsible for their assessment and application to their organisations.

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NHS Estates Technical Bulletin (NETB 2023/01B): application of ultraviolet (UVC) devices for air cleaning in occupied healthcare spaces: guidance and standards

Publication (/publication)

Content

Applicability

This NETB applies to all healthcare spaces with ventilation requirements.

Objective

To provide additional technical guidance and standards on the use of UVC devices for air cleaning in healthcare spaces.

Status

The document represents advice for consideration by all NHS bodies. It is to be read alongside Health Technical Memorandum 03-01 Specialised Ventilation for Healthcare Premises (HTM 03-01) (https://www.england.nhs.uk/publication/specialised-ventilation-for-healthcare-buildings).

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Executive summary

Ventilation* is a key line of defence for infection control in the healthcare environment. Its design and operation are described in Health Technical Memorandum (HTM-03-01) (https://www.england.nhs.uk/publication/specialised-ventilation-for-healthcare-buildings/). The current focus on ventilation has highlighted areas of high risk due to poorly performing and inadequate ventilation in hospitals and other healthcare settings due to age, condition of air handling plant, lack of

maintenance, challenges with effective use of natural ventilation or other creates areas of high risk. It is therefore important to bring these facilities up to the minimum specification of current standards, particularly recognising the challenges of COVID-19 and other respiratory infections.

Ultraviolet (UVC) air cleaners (also known as air scrubbers) using ultraviolet light are one option for improving and upgrading ventilation. The installation of a UVC air cleaner can reduce the risk of airborne transmission.

This document has been written as an interim specification to set the basic standard required for UVC devices to be utilised in healthcare and patient related settings. This edition is primarily aimed at portable and semi fixed (wall-mounted) devices. The series will extend to in-duct and upper room devices in future iterations. Devices relying on HEPA filters or similar filter-based technology can have similar benefits to UVC devices but are not considered in this document. The potential of air scrubbers employing UVC or HEPA technology is the subject of a rapid review (September 2022) (https://doi.org/10.1101/2022.10.25.22281493).

*Ventilation is the process by which 'fresh' air (normally outdoor air) is intentionally provided to a space and stale air is removed. This may be achieved by mechanical systems using ducts and fans, or natural ventilation most commonly provided through opening windows. The local redistribution of air may also be construed as ventilation.

1. Introduction

Ventilation is a critical feature in the control of airborne infection. However, the emergence of SARS-CoV-2 as a highly contagious virus has demanded new and innovative solutions to safeguard patients, staff and visitors. Health Technical Memorandum 03-01 Specialised Ventilation for Healthcare Premises (HTM-03-01) is a robust standard for ventilation of higher risk clinical spaces based on high air change rates using outdoor air to continually flush indoor spaces. The emergence of COVID-19 has shown that greater attention must be paid to the removal or deactivation of airborne pathogens in areas where ventilation rates are lower.

The focus on ventilation has also highlighted areas of high risk due to poorly performing and inadequate ventilation, particularly in older hospitals and other healthcare settings such as primary care and dental, which increase risks of infection spread viz nosocomial infections.

In cases, where current ventilation does not meet HTM-03-01 standards, this may be due to age, condition of air handling plant, lack of maintenance or other design or operational issues. In the case of naturally ventilated spaces, there is a reliance on staff or patients opening windows. Weather conditions, external noise and air pollution and restricted window openings for safety affect the ability to open windows and means that ventilation in some settings can fall below recommended rates.

UVC air cleaners using ultraviolet light are one option for improving and upgrading ventilation. The correct installation and operation of a UVC air cleaner can effectively reduce the risk of airborne transmission.

NHS trusts are under pressure to improve ventilation and are considering options including UVC air cleaning. This standard will assist trusts in selecting and implementing good quality, reliable equipment.

There is substantial evidence from laboratory studies and real-world settings that UVC is an effective technology for reducing airborne pathogens within room air and HVAC systems. A number of trial 'case studies' have been carried out which indicate that measured levels of microorganisms in air are greatly reduced and infection rates have decreased.

These trials have also shown that UVC within HVAC systems safely allows some levels of air recirculation and can achieve substantial energy reductions compared to the normal 100% fresh air approach set out in HTM-03-01. For example, a scheme with 50% fresh air and 50% recirculated air would reduce heat demand by 50%. However, care must be taken to ensure sufficient fresh air changes are provided for the dilution of medical gases and noxious odours, and the maintenance of appropriate oxygen and carbon dioxide levels.

This document aims to serve as interim guidance and regulatory reference point for the design and correctly engineered deployment of germicidal UVC devices in real-world settings with regard to effectivity and safety.

2. UVC germicidal effects

There are a wide range of UVC devices which aim to inactivate microorganisms in the air and/or on surfaces. This document focuses on contained UVC devices which can be positioned locally within a room or within an HVAC duct. These devices usually require fan assisted circulation to introduce the room air into the device, expose it to ultraviolet light and then to reintroduce the processed air into the room. Therefore, aerodynamics internal to the device together with the lamp specification determines the air and microbial particle UVC exposure time and hence the radiation dose.

These devices are known as active UVC air cleaning devices. Not considered in this document are passive UVC devices, aka upper room devices, which rely on the natural air currents within rooms.

An important consideration regards the flow of the air which is induced, processed and distributed by the device external to the device itself. The design and placement of the device should promote efficient air circulation in the room space and avoid short-circuiting of air circulation relative to furniture, obstructions, and occupancy.

The ultraviolet-C (UVC) spectrum lies in the interval [200…280] nm. UVC irradiation as a means of microbial inactivation has been used for over 100 years in multiple sectors including medical, scientific, water disinfection, manufacturing and agricultural.

UVC germicidal activity inactivates microorganisms rendering them unable to replicate. Most commonly, germicidal activity is generated by mercury ionisation lamps with the major spectral line at 254 nm wavelength. This is sometimes also known as germicidal ultraviolet (GUV) or ultraviolet germicidal irradiation (UVGI). This standard uses the term UVC.

Recent studies suggest that devices based on far-UV (222 nm wavelength) may also be effective; however, these are not covered here.

The photo-toxicity risks associated with UVC is universally recognised. The design, specification and implementation of germicidal UVC solutions currently lacks rigorous governance and the requirement for regulatory change is recognised. The purpose of this standard therefore is to establish the key criteria for successful and reliable long-term application of UVC air cleaning while avoiding the potential safety hazards and operational pitfalls, particularly when equipment is used in spaces occupied by non-technical people.

3. Applications

This standard covers the types of UVC air cleaners used as standalone or in-duct units where the principal active element is UVC at the nominal wavelength of 254 nm.

In rooms without natural or mechanical ventilation, or where the ventilation falls short of local requirements or regulatory advice, auxiliary devices may be deployed to enhance the effective air changes. The installation of UVC air cleaners can be considered to contribute additional ‘equivalent’ air changes (eACH). For example, a treatment room with only 2 ACH could achieve the equivalent of 10 ACH by installing a UVC unit which recirculated and cleaned the equivalent of 8 ACH (eACH) for the microorganisms of concern. Hence, to meet the requirements that comply with HTM-03-01, the number of devices required will be dictated by the existing background levels of ventilation.

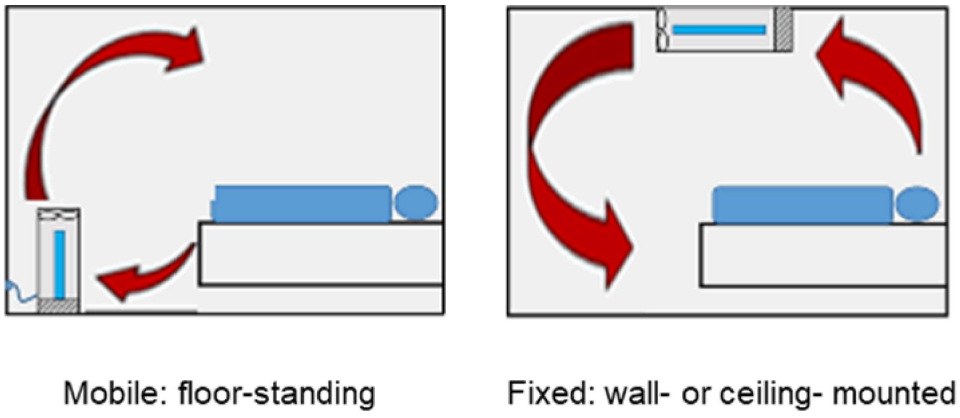
In-duct HVAC systems

In buildings with existing HVAC systems which have recirculation of air, it can be effective to install UVC lamps directly into the ducts, placing them downstream of pre-existing particulate filters. This allows for the treatment of all rooms in the building covered by the HVAC system or within branch ducts serving various zones and the rooms within those zones.

Due to the lamps being contained within the ducts, the risk of direct exposure to UVC is low. However, maintenance can be carried out safely shut-down interlocks should be fitted and hazard notices compliant with BS EN ISO 7010 prominently displayed.

Standalone devices

Standalone devices maybe portable (floor-standing) or fixed (wall- or ceiling-mounted).



(https://www.england.nhs.uk/wp-content/uploads/2023/05/standalone-devices.png)

Figure: Representation of air flows with respect to a recumbent patient in a regular room for 2 device locations. i. mobile: floor-standing; ii. fixed: wall- or ceiling-mounted.

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254 nm devices covered in this standard

- **In-duct UVC:** UVC lamps are installed directly into the HVAC system or are contained within a locally installed ventilation device which is connected into the HVAC system, similar to a fan-coil unit. Devices may use the fans and filters within the existing HVAC system or, in some cases, may have local fans and filters to provide the recirculation. Significant modelling and design are required to implement such systems.
- **Floor standing UVC 'mobile' devices:** UVC lamps are contained within a standalone floor mounted device that can be positioned at any suitable location in a room. These devices provide local air cleaning within a room and are plugged into a standard electrical socket so do not require any installation. The device contains lamps, dust filters and a fan to draw room air through the device. Devices are portable and so can be easily moved.
- **Fixed UVC devices – wall or ceiling mounted:** Similar to floor standing units but fixed to a wall or ceiling. These devices will normally be permanently wired into the room electrical system rather than plugged into a wall socket.

UVC devices not covered in this standard

- **Decontamination UVC devices:** High intensity open-field UVC devices that are designed for periodic surface decontamination in unoccupied spaces. These devices are sometimes known as UVC robots.
- **Upper-room UVC devices:** UVC devices which utilise an open UV field within the room above the heads of occupants. These are passive devices which rely on the general circulation of room air and are sometimes assisted by ceiling fans.
- **Devices based on other parts of the UV spectrum:** The devices covered in this standard are based on 254 nm wavelength lamps. There are a number of other UV technologies including Far UV (222 nm) which has early data showing it is likely to be effective.
- **Devices that incorporate other technologies alongside UVC:** There are a number of devices which use UVC alongside other technologies such as titanium dioxide catalysts or ionisers. These devices often emit by-products into the room, either intentionally or deliberately. The health impacts of any emissions must be carefully considered.

4. Safety

4.1 Accidental exposure

Safety is of paramount importance when working with UVC devices. Direct exposure to UVC light can cause damage to the skin and eyes.

The manufacturer of a germicidal UVC device should provide assurance in the device specification that the maximum UV (total) irradiance at 20 cm distance from any part surface of the device is ≤1 $mW.m^2$ (noting that this is based on an accumulated exposure of 8 hours). Exposure limits to UVC are specified in the directive Control of Artificial Optical Radiation at Work Regulations (AOR) 2010 (https://www.legislation.gov.uk/uksi/2010/1140/made).

Fail-safe systems are required to prevent lamps from operating when the cover of the device is removed.

4.2 Wider safety considerations

Care needs to be taken during maintenance and in operation that lamps are not broken. Appropriate safety protocols need to be in place to minimise risk of exposure to mercury vapour where devices contain mercury based lamps.

As electrical devices, UVC devices must comply with the Low Voltage Designated Standards (Electrical Equipment (Safety) Regulations 2016) (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1096713/ds-0061-22-low-voltage-equipment-notice.pdf).

Manufacturers should be aware that wiring and other components are liable to degradation under UV radiation.

5. Engineering implementation

5.1 Regulatory and standards compliance

Standards are an integral part of product design and development and are important in medical applications. The Low Voltage Directive (section 5.1.2 (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#5-engineering-implementation)) should be followed implicitly as a minimum. There are other standards and regulations which apply when using UVC air cleaning devices.

IEC 60601 is a series of technical standards which apply to medical electrical equipment and medical electrical systems for basic safety and essential performance. The basic scope of IEC 60601 -1 is the safety of patients and users. While compliance to IEC 60601-1 is not mandated in this standard, the design of standalone germicidal UVC devices should follow the principles of the 6061 standard to ensure risks to patient and user safety within a medical environment are recognised and mitigated (section 5.1.2 (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#5-engineering-implementation))

5.1.1 CE and UKCA marking

CE and UKCA marking are standards that appear on products traded on the extended single market in the European and UK economic areas. The marking signifies that the product has been assessed to meet high health, safety and environmental requirements.

- Selling products in Europe:
  - use of the CE-mark declares that the product meets the legal requirements for sale throughout the European Union.
- Selling products in the UK:
  - the UKCA-mark is the product marking used for products being placed on the market in Great Britain (England, Scotland and Wales)
  - the UKCA-mark applies to most products previously subject to the CE- marking. The technical requirements (sometimes referred to as 'essential requirements') must be met.

5.1.2 Electrical safety

- Compliance with the Low Voltage Directive is mandated implicitly.
- Compliance with the IEC 60601-1 standard is explicitly mandated.
- Class I (exposed metal components connected to earth):
  - protective earth continuity <0.2 MΩ.
  - insulation tests: ≥50 MΩ
  - earth leakage: ≤5 mA in normal condition (NC), ≤10 mA in SFC (single fault condition)
  - enclosure leakage current: ≤1 mA in NC, ≤0.5 mA in SFC
- Class II (double-insulated enclosure):
  - insulation tests: ≥50 MΩ.
  - enclosure leakage current: ≤0.1 mA in NC, ≤0.5 mA in SFC

Class III devices are not recommended.

5.1.3 Electrical wiring

Electrical wiring should be in accordance with IET Regulations BS 7671:2018 Requirements for Electrical Installations (https://electrical.theiet.org/bs-7671/).

Electrical components which are contained within a UVC device must be selected appropriately. Wiring and connectors should not be exposed to direct high intensity UV light. However, where exposure is unavoidable, secondary UV-resistant sheath should be employed. Exposed cables, particularly any with PVC coverings, will deteriorate due to the effect of UVC light.

5.1.4 Optical radiation safety

Safety is of paramount importance when working with UVC devices. Direct exposure to UVC light can cause damage to the skin and eyes.

The manufacturer of a germicidal UVC device should provide assurance in the device specification that the maximum UV (total) irradiance at 20 cm distance from any part surface of the device is ≤1 $mW.m^2$ (noting that this is based on an accumulated exposure of 8 hours). Exposure limits to UVC are specified in the directive Control of Artificial Optical Radiation at Work Regulations (AOR) 2010 (https://www.legislation.gov.uk/uksi/2010/1140/made).

Fail-safe systems are required to prevent lamps from operating when the cover of the device is used.

5.2 Ozone hazard

Ozone (https://www.gov.uk/government/statistics/air-quality-statistics/concentrations-of-ozone), an allotrope of oxygen, can be produced when oxygen is exposed to UVC with a wavelength below 240 nm. Ozone above occupational exposure limits (UK Workplace Exposure Limit (WEL) of 0.2 ppm (15 minute reference period)) is harmful to human health and can affect the respiratory, cardiovascular and central nervous system. Ozone can also cause degradation of certain materials, which can lead to fire hazards.

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Manufacturers shall provide assurance that devices do not produce ozone which contributes to room levels in excess of the WEL.

6. Engineering design, specification and performance validation

6.1 Characteristic specification (characteristic verification)

The manufacturer should provide a 10 mm diameter access port to the reaction chamber. This will enable the point measurement of air velocity and point measurement of UVC irradiance to provide assurance that the device is operating to the specification cited by the manufacturer under 'verification'. It is expected that this facility will be used during the annual maintenance check by the designated competent persons (section 7 (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#7-competent-persons)).

6.2 Bio-validation

The microbial inactivation rate for a UVC device, and hence the equivalent air change rate it provides, depends on the microorganism and the temperature and humidity. The manufacturer should provide evidence of the germicidal effectivity of their device at a given air flow (see above) and under given environmental conditions. At the present time, the preferred method of bio-validation (the Liverpool Biovalidation Protocol for the real-world evaluation of UVC-based air purifiers (NHS England Supply Chain)) uses *Micrococcus luteus* as the bacterial challenge under ambient environmental conditions of 23 C and a relative humidity of 50%. If an alternative protocol is employed, equivalence must be evidenced with reference to *k*, the UVC susceptibility constant for the particular microorganism (k, inactivation rate constant (susceptibility rate) [$cm^2.mJ^{-2}$]).

Where devices are used in settings where particular pathogens are likely to pose hazard, it is important to ensure that the susceptibility of the pathogen to UVC is taken into account when selecting a device.

6.3 Lamp guidance

At the time of publication, the most common source of UVC radiation is the mercury-vapour lamp (*aka* the mercury gas-discharge lamp). These devices are designed to emit at the wavelength 254 nm. While other technologies are available, *eg.* light emitting diodes (LEDs) and amalgam-mercury based discharge tubes, they are not considered here. Lamps should have anti-static surface coatings to minimise the build-up of surface contamination.

6.3.1 Effective life span

Lamp lifespan should be optimised to minimise replacement times and allow for a straight-forward replacement schedule.

Lamps should have an effective operational life of no less than one year (circa 8,800 hours for 24/7 active operational life) before they need replacing. Typically, the optical efficiency of a mercury-vapour lamp will decrease by 20% over its effective life span.

6.3.2 Operating conditions

The efficiency of a mercury-vapour lamp is affected by ambient temperature. Manufacturers should provide assurance that devices deliver their germicidal potency, as claimed, over an environmental operating temperature range of [10 …35] C.

6.3.3 Lamp failure indication

An alarm (visual and/or audible) should be implemented to notify of lamp failure.

6.4 Noise considerations

Devices in normal operation in occupied areas should operate at a sound level of ≤50 dB measured at 3 m (dB_{3m}). Exceptionally, for operation at boost, such that might be used to purge a room with controlled occupancy, the sound level should not exceed $60dB_{3m}$

Noise is a particular consideration when devices are used in rooms where patients are sleeping, and lower sound levels than stated here may be required depending on local environmental conditions. Further guidance on wider considerations around acoustics in healthcare is given in HTM-08-01 (https://www.england.nhs.uk/publication/health-sector-buildings-acoustic-design-requirements-htm-08-01/).

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7. Competent persons

In the present context, competent persons are recognised as individuals with professional expertise in one or more of the following areas in the healthcare setting: the design of UVC systems, the technical maintenance of UVC devices and systems, and the implementation of air sanitization schemes employing germicidal UVC.

Further, competent persons with particular expertise in infection prevention and control are essential to identify the relevant target microorganisms that UVC devices will need to mitigate.

8. Engineering and operational considerations

8.1 Hazard, risk and operational delivery

A ventilation design incorporating UVC-based air cleaners will require a hazard and operational study (HAZOP). This process will be convened by the Ventilation Safety Group (a group of individuals with recognised expertise in the design and operation of ventilation devices and systems responsible for the governance of the device deployments, as defined in HTM 03-01) which will include competent persons (section 7 (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#7-competent-persons)) including representation from infection and prevention control, nursing and estates management and/ or clinical engineering.

8.2 Conventional HVAC filters

Filters should be included into UVC systems to protect the UV lamps from dust build-up such that UV fluence is not compromised. Some devices may also contain carbon filters to mitigate odour and VOCs. In normal operation, the replacement period for such filters should not be less than one year. In exceptional circumstances, such as operation in areas with high levels of large particulate contamination, more regular replacement may be required to ensure air flow is not restricted. Local Standard Operating Procedures (SOPs) should be applied.

8.3 Ventilation effectiveness

The Ventilation Safety Group (HTM 03-01) (https://www.england.nhs.uk/publication/specialised-ventilation-for-healthcare-buildings/) will consider air flow strategies which achieve the most effective ventilation of occupied spaces. This requires that all factors such as air flow rate, mixing and distribution, dilution, thermal buoyancy and the impact of occupant movements must be considered.

8.3.1 Computational fluid dynamics (CFD) modelling of air movement

CFD modelling can be a useful tool to assist ventilation engineers to assess airflow patterns in the rooms where UVC devices are to be used and to identify the optimal locations to place devices. CFD modelling requires specialist knowledge, any simulations should be carried out by a competent person. CFD simulations can illustrate typical airflow patterns but may not be able to capture all of the fluctuations that occur in real environments, particularly those that are naturally ventilated.

8.4 Installation

The installation of any UVC air scrubbing devices should comply with all local building and electrical guidance. Advice should be sought from competent persons (section 7 (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#7-competent-persons)) including representation from infection and prevention control, nursing and estates management and/ or clinical engineering.

When positioning portable units engineers should consider the manufacturer’s recommendations around the best positioning to maximise the effectiveness, as well as practical considerations around space available in a room and access to power supply, cable routes, *etc*. Units should be positioned so that they do not interfere with the provision of care or provide an obstruction.

Units should always be positioned so that there is effective airflow into and out of the device. Vent panels on devices should not be blocked by furnishings and devices should be designed such that objects cannot be placed on top to cover vents. Patient comfort should also be considered with devices positioned such that they do not create uncomfortable draughts

Portable units can be a trip hazard in some locations and need to be positioned to ensure they or their cables do not pose a risk and do not impede access. Consideration should include risks for people who have visual impairments or restrictions on their mobility.

Consideration should be given to whether portable devices could be deliberately or accidentally moved or pushed over by patients or visitors. Device design should be stable and not easily toppled. In some settings it may be prudent to secure devices such that they cannot be moved.

8.5 Commissioning

Commissioning shall involve 'acceptance testing' according to local SOPs and include PAT testing to IEC 60601-1 (section 5.1.2 (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#5-engineering-implementation)). An audit of document compliance to the Low Voltage Directive (https://www.gov.uk/government/publications/designated-standards-low-voltage) is to be recorded. Where medical device classification is claimed, regulatory compliance with ISO 13485 Class 1 should be evidenced.

8.6 Verification and validation of performance

Manufacturers should evidence claims of engineering specifications (verification) and efficacy (bio-validation) (section 6.2 (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#6-engineering-design-specification-and-performance-validation)). The air velocity and UVC irradiance in the reaction chamber should be characterised at an arbitrary point specified by the manufacturer (section 6.1 (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#6-engineering-design-specification-and-performance-validation)).

8.7 Training

Staff in areas supported by UVC air scrubbing devices should receive training on operational and safety issues. A mechanism should be in place such that staff can notify estates management and/ or clinical engineering departments of suspected device malfunction. In an NHS context, such training might be included in staff mandatory training programmes.

8.8 Labelling

All UVC air scrubbing devices should be labelled to inform users of operating procedures and potential hazards. Labels should serve to make users aware of how to interact with UVC devices. Explicitly, these should include a hazard label to ISO 7010 'Non-ionising radiation' and an indicative label 'Does not contain user-serviceable parts'.

9. Maintenance

Maintenance shall be conducted only by a designated competent person.

9.1 Cleaning

Cleaning of UVC lamps is not required during normal operation in most environments. However, if UVC lamps are used within environments that are particularly dirty, then cleaning might be necessary (section 8.2 (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#8-engineering-and-operational-considerations)). Only cleaning products in line with the UVC lamp manufacturer's recommendations should be used.

The outside surfaces of devices should be designed to be easily cleaned as part of standard cleaning regimes in the healthcare setting and should not have features which are prone to collecting dust and dirt. The device should be robust to cleaning materials.

9.2 Lamp replacement

After lamps have exceeded their active operational life, they shall be replaced. Old lamps shall be disposed of according to local SOPs (section 6.3.1 (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#6-engineering-design-specification-and-performance-validation)).

9.3 Annual checks

All mobile UVC devices should undergo annual checks to verify their continuing performance. These checks should include, but are not limited to, the following:

- visual inspection of external and internal
- PAT test (5.1.2 Electrical safety (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#5-engineering-implementation))
- check alarms simulate failures

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- check lamp run times and replace if necessary. (6.3.1 Effective life span (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#6-engineering-design-specification-and-performance-validation)).
- lean internals of the device.
- measure UVC irradiance level against manufacturer's characteristic-specification (8.6 Verification of performance (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#8-engineering-and-operational-considerations))
- replacement and safe disposal of any filters (8.2 Conventional HVAC filters (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#8-engineering-and-operational-considerations))
- check air flow rate measurements at different speeds against manufacturer's characteristic-specification (8.6 Verification of performance (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#8-engineering-and-operational-considerations))
- check for UVC light spillage (4.1 Accidental exposure (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#4-safety))
- check noise levels against manufacturer's characteristic-specification (6.4 Noise considerations) (https://www.england.nhs.uk/long-read/application-of-ultraviolet-uvc-devices-for-air-cleaning-in-occupied-healthcare-spaces-guidance-and-standards/#6-engineering-design-specification-and-performance-validation)
- apply annual check sticker.

10. Building Management System (BMS) module

The incorporation of a BMS module into UVC air scrubber devices is recommended to afford the assurance of effective operation and to support maintenance scheduling. Modules should be enabled with the BACNet* open protocol for interfacing with existing an BMS.

*BACnet is a communication protocol for building automation and control (BAC) networks using the ASHRAE, ANSI and ISO 16484-5 standards protocol.

Annex 1 – Historical reference to UVC effectiveness

Downes and Blunt demonstrate that sunlight prevents microbial growth:

- [H.1] Downes A, Blunt TP. Researches on the effect of light upon bacteria and other organisms. Proc R Soc Lond 1877; 26: 488-500 (https://emea01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.jstor.org%2Fstable%2F113427&data=04%7C01%7C%7Cb8bec46e1b4142daf87908d9c3b5

Gates shows UV-spectral dependency with peak effectiveness around 265nm:

- [H.2] Gates FL. A study of the bactericidal action of ultra violet light: III. The absorption of ultra violet light by bacteria. J Gen Physiol 1930; 14(1): 31-42 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2141090/).

Wells proves the concept of infection via the airborne route and demonstrates the ability of UVGI to inactivate airborne microorganisms:

- [H.3] Wells WF. On air-borne infection: study II. Droplets and droplet nuclei. Am J Hyg 1934; 20: 611-8.
- [H.4] Wells WF, Fair MG. Viability of B. coli exposed to ultra-violet radiation in air. Science 1935; 82: 280-1 (https://pubmed.ncbi.nlm.nih.gov/17792965/).

Riley and Wells classic experiment which demonstrated that TB is airborne and that UVC reduces transmission:

- [H.5] Riley RL, Mills CC, O'Grady F, Sultan LU, Wittstadt F, et al. (1962) Infectiousness of air from a tuberculosis ward. Ultraviolet irradiation of infected air: comparative infectiousness of different patients. Am Rev Resp Dis 85: 511–525.

10.1 Reading list: recent peer reviewed papers demonstrating UVC effectiveness

Laboratory chamber studies demonstrating effectiveness of upper-room UV devices:

- [R.1] Ko G, First MW, Burge HA. The characterization of upper-room ultraviolet germicidal irradiation in inactivating airborne microorganisms. *Environmental Health Perspectives*, 2002; 110: 95–101. doi: 10.1289/ehp.0211095 (https://doi.org/10.1289/ehp.0211095)
- [R.2] McDevitt JJ,Milton DK,Rudnick SN,First MW. Inactivation of Poxviruses by upper-room UVC light in a simulated hospital room environment. *PLoS One*, 2008; 3: doi:10.1371/journal.pone.000318 (https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0003186).

Efficacy of recirculating UVC units:

- [R.3] Corrêa TQ, et al. Efficiency of an air circulation decontamination device for microorganisms using ultraviolet radiation. *Journal of Hospital Infection* 2021; 115: 32–43. doi: 10.1016/j.jhin.2021.06.002 (https://doi.org/10.1016/j.jhin.2021.06.002)
- [R.4] Snelling WJ, Afkhami A, Turkington HL, Carlisle C, Cosby SL, Hamilton JWJ, et al. Efficacy of single pass UVC air treatment for the inactivation of coronavirus, MS2 coliphage and Staphylococcus aureus bioaerosols. *Journal of Aerosol Science 2022*; 164: 106003. doi: 10.1016/j.jaerosci.2022.106003 (https://doi.org/10.1016/j.jaerosci.2022.106003)
- [R.5] Lee LD, Delclos G, Berkheiser ML, Barakat MT, Jensen PA. Evaluation of multiple fixed in-room air cleaners with ultraviolet germicidal irradiation, in high-occupancy areas of selected commercial indoor environments. *Journal of Occupational and Environmental Hygiene* 2002; 19(1): 67-77. doi: 1080/15459624.2021.1991581 (https://doi.org/10.1080/15459624.2021.1991581).
- [R.6] Qiao Y, Yang M, Marabella IA, McGee DAJ, Aboubakr H, Goyal S, et al. Greater than 3-log reduction in viable coronavirus aerosol concentration in ducted ultraviolet-C (UV−C) systems. *Environmental Science and Technology* 2021; 55(7): 4174-82. doi: 10.1021/acs.est.0c05763 (https://doi.org/10.1021/acs.est.0c05763)

Reduction in infection rates using various UVC approaches:

- [R.7] Menzies D, Popa J, Hanley JA, Rand T, Milton DK. Effect of ultraviolet germicidal lights installed in office ventilation systems on workers' health and wellbeing: double-blind multiple crossover trial. *Lancet* 2003; 362(9398): 1785-91. doi: 10.1016/S0140-6736(03)14897-0 (https://doi.org/10.1016/S0140-6736(03)14897-0).
- [R.8] Leach T, Scheir R. Ultraviolet germicidal irradiation (UVGI) in hospital HVAC decreases ventilator associated pneumonia (https://www.ashrae.org/file%20library/technical%20resources/covid-19/ashrae-d-ny-c023.pdf). *Ashrae Winter Conference*, 2014
- [R.9] Escombe AR,Moore DAJ, Gilman RH, Navincopa M, Ticona E, Mitchell B, et al. Upper-room ultraviolet light and negative air ionization to prevent tuberculosis transmission. *Plos Medicine* 2009; 6: doi: 10.1371/journal.pmed.1000043 (https://doi.org/10.1371/journal.pmed.1000043).

Wider reading on UVC and air cleaning applications:

- [R.10] Wladyslaw Kowalski, Ultraviolet Germicidal Irradiation Handbook UVGI for Air and Surface Disinfection, 2009, Springer doi: 10.1007/978-3-642-01999-9 (https://doi.org/10.1007/978-3-642-01999-9)
- [R.11] SAGE-EMG paper on air cleaning devices in the context of Covid-19 (https://www.gov.uk/government/publications/emg-potential-application-of-air-cleaning-devices-and-personal-decontamination-to-manage-transmission-of-covid-19-4-november-2020)

Annex 2 – Acknowledgements

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Annex 3 – Glossary

- **Absorption (light):** Intake or retention of electromagnetic waves via conversion to heat, here: 254 nm wavelength radiation.
- **Active operational life:** A product's operational life is the period for which a product is in use before it becomes obsolete, in terms of UVC lamps it is typically 70% of original efficacy.

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- **Aerosol generating procedure (AGP):** An aerosol generating procedure refers to a health care treatment (eg dentistry/endoscopy) or event (cough/sneeze) which generates particulate matter referred to as droplets or aerosols.
- **Air changes per hour:** Air changes per hour (ACH) is the measurement at which air volume per hour is added to a room divided by the total volume of the room. It represents the number of complete air exchanges in one hour under perfect air circulation conditions. See also Equivalent air changes per hour.
- **Air circulation:** Mixing of the air from natural or mechanical ventilation sources inside an enclosure.
- **Air circulation efficiency (%):** A measure of the effectiveness of air circulation in a real enclosure with obstructions such as occupancy and furniture, compared with perfect mixing as quantified by ACH/eACH. CFD studies in hospital and high-street treatment rooms indicate that the air circulation efficiency can vary between 40% and 80% depending on the device placement and proximity of furniture, equipment and occupancy. Similar variance applies to AGP-clearance and therefore will affect fallow time.
- **Age of air:** Time (s/min/h) locally the air has been inside the enclosure/room at that location since entering from a fresh/clean/purified source (natural ventilation source, mechanical ventilation source or purification device). This is a useful measure of dead or recirculating air pockets in the enclosure volume.
- **Apertures:** Windows, doors and external vents connecting the enclosure to the outside atmosphere.
- **Biofilm:** Biofilms consist of a thin slime or dry layer (film) in which microorganisms (eg. bacterial or algae) are embedded. They form mainly in water systems, either on the surface of the water or on an interface with a solid phase. Inside the biofilms the embedded organisms are active and growing so that new microbes continuously are spread into the water. By this, for example, cooling systems and water reservoirs get steadily contaminated. Furthermore, on dying biofilms moulds and yeasts can settle down.
- **BMS (Building Management System):** A computer-based control system installed in buildings that controls and monitors the building's mechanical and electrical equipment such as ventilation, lighting, power systems, fire systems and security systems.
- **Building regulations**: Building regulations set standards for the design and construction of buildings to ensure the safety and health for people in or about those buildings. They also include requirements to ensure that fuel and power is conserved, and facilities are provided for people, including those with disabilities, to access and move around inside buildings. Current standards require that healthcare buildings conform to NHS standards. For ventilation NHS HTM-03 applies.
- **CFD (computational fluid dynamics):** Computer-based fluid dynamics modelling providing a means to simulate air flow combined with convective/buoyant/conductive/radiative heat transfer, particulate transport (aerosols and droplets) and turbulence.
- **Characteristic specification (Characteristic verification):** A measurable property of the device that can employed routinely by the user to provide assurance of device operation to the verification model. See Verification.
- **Clearance**: The relative removal of a contaminant usually expressed as %. See Log reduction.
- **Construction Design and Management (CDM) regulations**: CDM regulations are a set of health and safety regulations that apply to every construction project in Great Britain.
- **D90**: Dose of UV to inactivate 90% of a microbial population. See k value.
- **Decontamination:** Decontamination describes the reduction of pathogenic microorganisms to a safe level for human use. Technically, this means reduction by a minimum of 1 log step, meaning 90%.
- **Disinfectant:** Disinfectants contain ingredients which either kill or inhibit the growth of microorganisms. Disinfectants require sufficient application time and must be used at sufficiently strong concentrations. Some well-known disinfectants are alcohols (eg. isopropanol), hydrogen peroxide (H_2O_2), ozone (O_3) and tinctures containing iodine.
- **Disinfection:** The term disinfection is not clearly defined in a technical sense. Generally, for the purposes of this standard, it means a reduction of pathogenic microorganisms by a minimum of 3 log steps. Hence, the term 'UVC disinfection' describes the inactivation of at least 99.9% of a given pathogenic population with the aid of UVC technology.
- **Dose:** aka 'Radiant Exposure'. The irradiance absorbed per unit time. Explicitly UV dose ($\mu W \cdot s.cm^{-2}$) = UV irradiance ($\mu W.cm^{-2}$) × exposure time (s)
- **Electromagnetic spectrum:** The electromagnetic spectrum is the range of all frequencies of electromagnetic waves.
- **Electromagnetic wave:** An electromagnetic wave consists of an electrical and a magnetic field component. Unlike pressure waves, electromagnetic waves do not require a medium for propagation; their propagation speed depends on the medium, with propagation in a vacuum taking place at the speed of light. The best-known electromagnetic waves are probably those described colloquially as 'light'.
- **Emission:** The sending out of electromagnetic waves.
- **Emitter:** The source of radiation is defined as an emitter.
- **Epidemic:** A localised, heavily massed occurrence of an infectious disease. See also Pandemic.
- **Exposure time or dwell time**: Length of time for which a microorganism is exposed to UVC irradiation (in the context of this standard).
- **Equivalent air changes per hour, eACH:** Equivalent air changes per hour, or eACH, is a measure of the 'equivalent' amount of air that is cleaned by a UVC device as a ventilation rate of new outside-air changes would achieve in one hour. See ACH. Note that this applies to decontamination and does not obviate the need for meeting minimum fresh air standards.
- **Fallow time:** Time (s/min/hr) allocated to a treatment room without occupancy to allow for clearance of the room after a contamination event (eg an AGP) to recover safe levels for occupancy.

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- **FDA:** [Food and Drug Administration] – the FDA is the American federal agency responsible for food monitoring and drug licensing. It is subordinate to the Department of Health and Human Services.
- **Fluence:** The amount of irradiation ('dose') within an enclosed space to which the air being treated by UVC is subjected. Unit is mJ.cm-2.
- **Fungicide:** Chemical or biological agent for destroying fungal spores and moulds.
- **Germicidal:** Action destroying or deactivating a microorganism.
- **Germicidal ultraviolet/germicidal ultraviolet irradiation:** Referred to commonly as GUVC and UVC. Both are one and the same in that they refer to ultraviolet C spectrum light that is germicidal.
- **HACCP:** [Hazard Analysis and Critical Control Points] – a preventive system intended to ensure food, medicines and safety critical products safely from manufacture to the consumer.
- **Hazard assessment:** A hazard assessment is a thorough check of the occupational environment. The purpose of a hazard assessment is to identify potential risks and hazards in the area, as well as to identify appropriate safety measures to be used to mitigate, eliminate or control the identified hazards.
- **HAZOP:** [Hazard Analysis and Operational study] – a systematic way to identify hazards in a work process.
- **IAQ (Indoor Air Quality):** A generic term used for air quality in enclosed spaces, usually referring to the combination of harmful gases (eg. CO2 and CO levels measured in parts-per-million, ppm), temperature (for thermal comfort), total volatile organic content (TVOCs measured in parts-per-billion, ppb), relative humidity (%) and particulate matter size (respiratory irritants/hazards) measured in microns-diameter, eg. PM2.5, PM10.
- **Inactivation:** Prevention of microbial replication.
- **Infection:** The process by which pathogens penetrate the body of an organism and multiply therein. Depending on the transmission route, we distinguish between contact infections and airborne infections.
- **Infectiousness:** Measure for describing the ability of a pathogen to cause actual infection in a host after transmission occurs.
- **Intensity:** In physics, 'intensity' describes energy density with respect to area.
- **Ionising radiation:** Ionising describes the type of radiation capable of permanently removing electrons from atoms or molecules. Note: UVC radiation has no ionising power (See also Technology – generating UVC rays).
- **IP rating:** [Ingress Protection] – types of protection that are classified according to IEC standard 60529. The letters IP are followed by two digits, the first indicating the degree of protection afforded against the ingress of solid bodies, and the second describing the degree of protection against the ingress of water.
- **k value:** Inactivation rate constant (susceptibility rate) k = (-ln(1-0.9))/D90. Units cm2.mJ-1.
- **Lethal dose:** Lethal dose (LD) is the term referring to the dose of a toxin or radiation which is deadly or inactivates an organism (this term includes microorganisms).
- **LD 90:** LD 90 is the dose which eliminates or inactivates on average 90% of an organism's population.
- **Lethality:** Lethality describes the ratio of deaths/eliminations/inactivations to survivals after a dose of radiation, infection, or illness viz the 'mortality rate'.
- **Living organism:** In biology, life forms capable of metabolic processes, replication and evolutionary development (all three criteria must be fulfilled) are known as living organisms.
- **Log:** [common logarithm] – although the term 'log' is the usual abbreviation for base-10 logarithms, the mathematically correct term here is log10. We speak here of decadic logarithms.
- **Log reduction:** The reduction of a contaminant can be quantified in log stages. A Log reduction of 'x number' therefore means a reduction by 'x number Log' stages starting from a given population. The reduction by 1 log stage means a reduction of 90%, since only 10% have survived from the original population. See Clearance.
- **Log stage (a.k.a. Log step):** A log stage or log step describes the reductio n of a population by a (further) power of ten: in other words, 1 log stage = 90%, 2 log stages = 99%, 3 log stages = 99.9%, etc. See Log reduction.
- **Melanoma:** Also known as black-mole cancer – a melanoma is a malignant tumour appearing as an asymmetrically growing, discoloured change in the skin.
- **Microorganism (microbe):** A microorganism is an organic structure so small that they can generally only be seen with the aid of a microscope and include viruses, bacteria and fungi. Such structures are usually single-celled, although they are occasionally multi-celled.
- **Monochromatic:** Describes radiation of a precisely defined wavelength, as, for example, emitted by a laser.
- **Mutation:** The changing of the structure of a gene, resulting in a variant form that may be transmitted to subsequent generations.
- **Nosocomial infection:** An infection contracted in a hospital or care institution.
- **Optical radiation:** The electromagnetic wavelength range between 100 nm and 1 mm is referred to as optical radiation. This includes ultraviolet radiation (UV), the visible light spectrum (VIS) and infrared radiation (IR).
- **Organism:** An organism is an individual life form. See Living organism.
- **Ozone:** Represented as O3. Ozone is a gas with strong oxidation properties that is toxic in low concentrations. Ozone can result from the oxidation of O2 irradiated by far UVC.
- **PAT (portable appliance testing):** Requirement of the Low Voltage Directive to demonstrate general electrical safety.
- **Pandemic:** A pandemic is an infectious disease of temporarily exceptionally high prevalence occurring across national borders. See also Epidemic.
- **Pandemic resilience:** Pandemic resilience is the ability to withstand, protect and recover quickly from any pandemic by ensuring infrastructure and buildings are equipped with the necessary safeguards to combat, eliminate or control pathogenic hazards that are so prevalent as to be classified as a pandemic or endemic hazard.

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- **Pathogen:** Pathogens are microorganisms capable of causing disease or illness in living creatures.
- **Prevention:** The taking of precautionary measures to stop undesirable occurrences.
- **Radiometer:** A radiometer serves to measure electromagnetic power These devices are generally based on photodiodes which convert the incoming radiation into a proportional electrical signal.
- **Radiometry:** Radiometry is the science of radiation measurement.
- Reflection: The (partial) return of electromagnetic waves at an interface. Reflection is the opposite of absorption. UVC air cleaners will be fitted with highly reflective materials within the air passageways in order to reflect and thereby amplify the amount of UVC in the air.
- **Residence time:** The average time taken by the air or airborne particles to pass through the UVC fluence zone. Unit seconds (s).
- **Sanitisation:** The process of reducing microbiological contamination. See Clearance and log reduction.
- **Sensitivity:** Here: responsiveness or susceptibility to UVC radiation. See k value.
- **SOP:** (Standard operating procedure) A set of step-by-step instructions compiled by an organization to help workers carry out routine operations.
- **Sound level: dB3m:** The acoustic power represented by dB measured at 3 m from the source.
- **Target:** A person, organism or thing that receives or is infected by an intervention.
- **Toxic:** The effect of a toxin is described as toxic. ‘toxic’ can also be defined as meaning ‘poisonous’.
- **Toxicity:** The degree to which a toxin is toxic or poisonous.
- **Toxin:** A toxin is a biogenic substance capable of damaging an organism by disrupting its physiological metabolic processes. The scientific discipline investigating toxins is called toxicology.
- **UV spectra:** The UV spectrum is commonly sub-divided into four regions:
  - Far UV or vacuum UV: [100…200] nm
  - UVC: [200…280] nm (NB germicidal UV)
  - UVB: [280…315] nm
  - UVA or near UV: [315…400] nm
- **Validation (bio-validation):** The process to provide assurance that the device is effective as claimed by the manufacturer. For the purposes of this standard, assurance that sanitisation is achieved as claimed.
- **Verification:** The process to provide assurance that the device performs to the manufacturer’s specification. For the purposes of this standard, assurance that air flow and UVC dose are as claimed.
- **Viruses:** Viruses are particles or information carriers dependent for survival and replication upon the metabolism of a host cell since they themselves have no cytoplasm and are incapable of metabolism. Viruses are thus, de facto, not living organisms.

The National Estates and Facilities team at NHS England is responsible for producing Standards and Guidance for the NHS estate and ensuring that the information and guidance they contain remains up-to-date and relevant for users.

NHS Estates Technical Bulletins (NETBs) enable updated guidance to be passed to local systems, ensuring we maintain our focus on patient safety. NETBs contain technical guidance and standards which systems and organisations are required to consider and implement, where applicable. Boards are responsible for their assessment and application to their organisations.

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