UK Covid-19 Inquiry

Module 3 – the impact of the Covid-19 pandemic on the healthcare systems of the UK

An expert report on the physical sciences underpinning Covid-19 transmission and its implications for infection prevention and control in healthcare settings

Author: Professor Clive Beggs PhD, PhD, FIMechE, FRSB

Author statement

"I confirm that this is my own work and that the facts stated in the report are within my own knowledge. I understand my duty to provide independent evidence and have complied with that duty. I confirm that I have made clear which facts and matters referred to in this report are within my own knowledge and which are not. Those that are within my own knowledge I confirm to be true. The opinions I have expressed represent my true and complete professional opinions on the matters to which they refer."

Clive Beggs

7th August 2024

Contents

Preamble

- This report has been prepared by Professor Clive Beggs for Module 3 of the Covid-19 Inquiry. It details the physical science underpinning the transmission of SARS-CoV-2, influenza and other respiratory viral infections in healthcare facilities, as well as the use of non-pharmaceutical interventions (NPI) such as face masks, respiratory protective equipment (RPE) and room ventilation.

- Prof. Beggs is a bio-engineer (*Fellow of the Institution of Mechanical Engineers*) and physiologist (*Fellow of the Royal Society of Biology*), who is Emeritus Professor of Applied Physiology at Leeds Beckett University. He is a multidisciplinary scientist who has spent more than 25 years researching the transmission of infection in hospitals, as well as working in neurology. He specialises in interdisciplinary research, and has particular expertise in: (i) the transmission of infectious disease in hospitals; (ii) ventilation and the behaviour of aerosols in air; (iii) biophysics and the application of engineering interventions to mitigate the transmission of infection; and (iv) the role of fluid dynamics in the progression of neurodegenerative disease (multiple sclerosis, vascular dementia, etc.). He is also a mathematical modeller, with particular expertise in machine learning and data science, which he uses in his clinical research work.

- Before entering academia, Prof. Beggs worked as a professional engineer designing ventilation and air conditioning systems for buildings, and as such, has an intimate knowledge of hospital ventilation systems. After entering academia, he pioneered interdisciplinary research at the interface between engineering and microbiology. In 1998, while at the University of Leeds, he founded the *Leeds Aerobiological Research Group* (later part of the *Pathogen Control Engineering Research Institute* headed by Prof. Catherine Noakes), before going on to establish (in 2005) the *Bradford Infection Group* at the University of Bradford. He has also worked with other clinical research teams around the world (University of Ferrara, University of Buffalo, Queensland University of Technology, etc.) and has published widely. Now in an emeritus position, Prof. Beggs continues to work with teams at Queen Mary University of London and Addenbrooke's Hospital, Cambridge, on projects relating to the transmission SARS-CoV-2 and other pathogens.

- During the Covid-19 pandemic Prof. Beggs served on the Royal Society *Rapid Assistance in Modelling the Pandemic* (RAMP) working group, and was instrumental (securing funding, designing, managing, etc.) in establishing: (i) the Class-ACT study in Bradford, investigating the use of air cleaning technologies (HEPA filters and UV air disinfection) to mitigate transmission of SARS-CoV-2 in schools (a collaboration between the UKHSA, DfE, University of Leeds, and Queen Mary University of London); and (ii) the AAirDS study, investigating the use of HEPA filters to mitigate transmission of SARS-CoV-2 and other pathogens on two medicine for the elderly wards at Addenbrooke's Hospital (a collaboration between the UKHSA, Addenbrooke's, and the University of Cambridge). In addition, during the pandemic, Prof Beggs provided independent advice to the *Department of Health and Social Care* (DHSC), *Department for Education* (DfE), and the *Chartered Institution of Building Services Engineers* (CIBSE) on matters relating to Covid-19 transmission in buildings.

- This report is an expert witness statement, and as such, the opinions expressed are those of Prof. Beggs based on his knowledge of the subject and research experience. Where Prof. Beggs refers to his own published research work it is denoted with an asterisk. Where he talks about his own personal experience, this is denoted by the use of 'the author' in the text, to refer to himself.

- Prof. Beggs is a research scientist and not a clinician, therefore this report concentrates on the physical science aspects of SARS-CoV-2 and influenza transmission in healthcare facilities, rather than on the clinical treatment and care of patients. Where interventions, such as facemasks, are mentioned, these are discussed in terms of the physical science associated with their use, rather than their clinical application and everyday use. Similarly, when discussing policy, the report focuses on the scientific evidence and consensus that pertained at the time, and highlights errors and misconceptions relevant to events in Covid-19 pandemic.

- For the most part the report covers topics in which Prof. Beggs is an expert. However, in places, for completeness, the report may cover topics in which Prof. Beggs has less expertise. Where this is the case, this will be expressly stated, with the term 'limited expertise' inserted in the text to inform the reader. Where a topic falls outside of the expertise of Prof. Beggs, this will be clearly stated in the text, with the reader directed to the UK Covid-19 Inquiry's clinical expert report on infection prevention and control (IPC) by Professor Dinah Gould, Dr Ben Warne, and Dr Gee Yen Shin.

Introduction

1. This report details the physical science underpinning the transmission of SARS-CoV-2, influenza and other respiratory viral infections in healthcare facilities, as well as the use of non-pharmaceutical interventions (NPIs) designed to reduce transmission, such as facemasks, respiratory protective equipment (RPE), air cleaners, and room ventilation. As such, the aims of the report are:

    (i). To explain the state-of-the-art physical science (i.e., exhalation, transport, survival, etc.) associated with the transmission of SARS-CoV-2 and influenza in respiratory particles, and also by the contact and fomite routes.

    (ii). To evaluate the evidence for the various routes of transmission of SARS-CoV-2 and influenza, and describe how the scientific consensus on this subject evolved over time.

    (iii). To explain the long-standing historical controversy surrounding droplet and aerosol (airborne) transmission of respiratory viruses, and to highlight errors in thinking (misconceptions) on this subject that persisted amongst many medical and infection prevention and control (IPC) professionals, and which shaped policy going into the Covid-19 pandemic.

    (iv). To explain the ramifications of these misconceptions on IPC policy and practice, and highlight the implications of this going forward.

    (v). To explain the physical science underpinning the use of facemasks, face visors, and RPE in hospitals, and evaluate the evidence supporting their use.

(vi). To explain the physical science underpinning the ventilation of hospital buildings, and the use of supplementary air cleaning devices to mitigate the transmission of infection in clinical settings.

(vii). To evaluate current NHS ventilation and air cleaning guidelines, and highlight the IPC shortcomings associated with these.

(viii). To identify lessons learnt from the Covid-19 pandemic, as well as gaps in the knowledge base, and to make recommendations regarding future research that should be undertaken.

2. The report is structured in such a way as to aid the reader in understanding the subject matter. The first portion (Part 1) explains in detail the state-of-the-art physical science associated with the transmission of respiratory viruses, and the evidence supporting this. This includes transmission by the respiratory (traditionally divided into droplet and airborne (aerosol)), contact (hand touch) and fomite (surface) routes. Although the same physical science broadly applies to all respiratory viruses, the focus of this report is on the transmission of SARS-CoV-2 and influenza. Asymptomatic transmission and superspreading events are also discussed.

3. The historical controversy surrounding airborne and droplet-borne diseases is discussed in detail in Part 2, with errors in the scientific thinking on this subject highlighted and explained. The far-reaching implications of these historical errors on policy and practice are also discussed, together with an explanation of how the scientific consensus on this subject evolved over time.

4. In Part 3 of the report, attention is turned to the physical science associated with facemask and RPE use in hospitals, with the evidence supporting their use evaluated. Knowledge gaps in understanding relating to these protective devices are also discussed, together with inconsistencies between science and policy.

5. Part 4 is concerned with the ventilation of hospital buildings and supplementary air cleaning. Here the current NHS guidelines (which were active during the Covid-19 pandemic) are evaluated in the light of the shift in scientific consensus that emerged during the pandemic.

6. Finally, in Part 5, lessons learnt from the Covid-19 pandemic regarding the transmission of respiratory viruses are considered. Gaps in the knowledge base are also discussed, together with recommendations for future research to address these.

7. Throughout the report, key findings boxes are inserted in the text, which briefly summarise the important 'take-home' messages for the relevant sections.

8. Importantly, this report does not cover (other than tangentially) clinical practice, and IPC matters relating to the screening, nursing, isolation and treatment of patients, which are covered in the UK Covid-19 Inquiry's clinical expert report on IPC by Professor Dinah Gould, Dr Ben Warne, and Dr Gee Yen Shin. This report also does not cover the regulatory framework for personal protective equipment (PPE) use in UK healthcare settings.

Part 1: Transmission of infection

9. In Part 1 the state-of-the-art physical science associated with the transmission of respiratory viruses is discussed, with the evidence for transmission by the droplet, aerosol (airborne), contact (hand touch) and fomite (surface) routes evaluated. Asymptomatic transmission and superspreading are also discussed.

10. One major problem that has greatly inhibited understanding of the transmission of respiratory viral infections, has been the historical confusion surrounding the size and behaviour of respiratory particles that are exhaled (see Part 2 for details). In part, the problem arises from the terminology used by different scientific disciplines to describe these particles, with the medical community using the terms 'droplet' and 'droplet-nuclei' (which are inconsistent with the aerosol science associated with the behaviour of small particles in air), whereas physicists and engineers, more correctly, use the terms 'large droplets' and 'aerosol particles'. While this might appear a superficial distinction, it is actually not a trivial matter, because ultimately it has resulted in many incorrect beliefs about the transmission of SARS-CoV-2 and influenza (Tang et al. 2021a).

11. As a result of scientific advances made during the Covid-19 pandemic, attempts are now being made to clarify the terminology that should be used, with a global group of experts convened by the World Health Organisation (WHO) recommending (April 2024) that "*pathogens that transmit through the air*" should be used instead of the older terminology (WHO 2024a). While this attempt to clarify the terminology is welcome, "*pathogens that transmit through the air*" is a rather catch-all phrase that does not accurately reflect important physical distinctions and characteristics that can have a profound impact on the transmission of infection. The WHO's expert group split this further into the *"direct deposition"* and *"airborne transmission/inhalation"* routes, but did not state which pathogen species are in each category (if indeed they can be dichotomised in this way), stating the need for further research. As such, the WHO's proposed new terminology is still somewhat confusing and controversial (Greenhalgh et al. 2024b). **So, in this report, the established terms adopted by physicists and engineers will be used, namely: 'large droplets', referring to respiratory particles larger than about 100 micrometres (100µm) diameter; and 'aerosol particles', for all other exhaled particles less than 100µm diameter, after they have undergone evaporation (see paragraphs 24 to 37 for details).** These terms are used here because they accurately reflect the physical science associated with the exhalation and transport of respiratory particles. However, when referring to all exhaled particles (which includes both larger droplets and smaller aerosol particles) the generic term 'respiratory particles' will be used.

The chain of infection

12. In this section the fundamental concepts involved in the transmission of respiratory viral infection are explained, with the focus on SARS-CoV-2 and influenza. Although primarily concerned with these two viruses, the discussion is also relevant to the bacterial infection, tuberculosis (TB). It has been widely accepted by scientists for decades that TB is transmitted by the airborne route, and it is a major worldwide problem, with an estimated 2 billion people thought to be infected (CDC 2024b). This section is also relevant to the transmission of other respiratory viral infections, such as respiratory syncytial virus (RSV), which in theory can be spread via aerosol particles, although epidemiological evidence supporting this route of transmission is incomplete.

13. In order for a viral infection to be transmitted in humans or animals, viable virus particles (also called 'virions') must be transported from an infectious individual (or "infectious host") to a susceptible individual ("susceptible host"). However, when these virus particles eventually reach a susceptible host, they may not cause any disease, simply because they might not come into contact with the receptors on the host's cells that facilitate infection. These target receptors are different for various viruses. For example, with Covid-19, the targets are the angiotensin-converting enzyme 2 (ACE2) receptors, whereas for influenza, sialic acids are the primary receptors (Ramos & Fernandez-Sesma 2012). Although target receptors vary between viruses, the general principles involved are the same, with the virus particles needing to bind to the target receptors in order to initiate an infection. Furthermore, even when virus particles do manage to engage with the target receptors and enter the host's cells, they often fail to cause infection because the host's immune system overwhelms them. So, for transmission to occur, sufficient numbers (e.g., several hundred (Prentiss et al. 2022)) of viable virus particles must come into contact with the susceptible host's tissue, in order for a few to engage the target receptors and evade the host's immune defences and successfully establish an infection (Bendall et al. 2023; Lythgoe et al. 2021; McCrone et al. 2018).

14. This means that in order for an infection to spread, infectious individuals must shed virus particles into the environment in such numbers (generally thought to range from several hundred to many thousands, depending on the viral species and the context) that a few eventually reach the target receptors of a susceptible host, who once infected is then able to infect one or more other susceptible people to continue the chain of infection.

15. Viral diseases can be transmitted by multiple routes (Rutter et al. 2021), and so chains of infection can be short and direct (i.e., from host to host), as in the case of respiratory transmission, or alternatively be more complex and involve several indirect steps (e.g., faecal-oral or mosquito-borne transmission). However, irrespective of the route of transmission, IPC measures aim to interrupt the chain of infection, by either introducing barriers to transmission that prevent the virus from reaching its intended target (e.g., facemasks), or alternatively inactivating the virus *en route* so that it cannot cause an infection (e.g., disinfection of inanimate surfaces and objects). By doing so, the intention is to break the chain of infection and thus inhibit transmission of the disease.

16. Although the primary focus of this report is on respiratory transmission, it will also address transmission by touch (i.e., contact transmission). This occurs with many viral and bacterial pathogens (e.g., Ebola and MRSA) and historically has been thought to be one potential route by which respiratory viral infections are transmitted. The contact route can either be **direct**, where the infected person physically touches the susceptible person (e.g., a handshake), or **indirect**, where the infected person touches and contaminates a surface or object (e.g., a door handle), which is then touched by a susceptible person. Healthcare professionals refer to such contaminated objects as "**fomites**", with the term "**fomite transmission**" often used to describe the spread of infection that involves contaminated surfaces and objects.

17. However, it should be noted that when the term fomite transmission is used it can refer to a surface contaminated either by touch or by infectious droplets (i.e., large respiratory particles that do not behave as aerosols (see paragraph 57)) that land on it. With both direct and indirect transmission by touch, the final step usually involves the susceptible person transferring the virus from their hands to their nose, mouth or eyes. A full discussion of the role of touch and fomite transmission in the transmission of SARS-CoV-2 and influenza can be found in paragraphs 90 to 105. However, for contextual purposes, we point out here that during the

Covid-19 pandemic scientific opinion on this subject greatly changed, with the general consensus emerging that the contact and fomite routes are less important, with the inhalation of infectious aerosols now thought to make a major contribution to the transmission of SARS-CoV-2 transmission. Prior to the Covid-19 pandemic, the general consensus amongst the IPC community was that touch and fomite transmission played a much greater role in the spread of respiratory viral infections. However, this consensus was not shared by all scientists, with notable exceptions such as Don Milton (Milton et al. 2013; Yan et al. 2018), Ben Cowling (Cowling et al. 2013; Leung et al. 2015), Raymond Tellier (Tellier 2006; Tellier et al. 2019), Julian Tang (Tang et al. 2011) and William Lindsley (Lindsley et al. 2016; Lindsley et al. 2010b), all of whom published articles highlighting the important role of respiratory aerosols in the transmission of influenza (an opinion shared by the author of this report).

18. The role of exhaled respiratory particles in the transmission of SARS-CoV-2 remains a contentious issue with many IPC professionals still (August 2024) believing that it is the deposition of so-called 'droplets' on the mucosa of the nose, mouth and eyes that is the principal route by which Covid-19 is spread, whereas the overwhelming physical science evidence strongly indicates that the inhalation of infectious aerosol particles is the dominant route. The latter opinion was influential in changing the position of the WHO, who early in the Covid-19 pandemic stated categorically that the disease was **not** airborne (Lewis 2022; Morawska et al. 2023), but now (August 2024) acknowledges that the inhalation of infectious aerosols is likely **an important** route by which SARS-CoV-2 **** [see text below]** (WHO 2024a; WHO 2024b). Government bodies in the UK still have varied and ambiguous positions about this, with Appendix **11a** (https://www.england.nhs.uk/wp-content/uploads/2022/09/nipcm-appendix-11a-v2.7.pdf) in the *National infection prevention and control manual (NIPCM) for England* describing the transmission route for SARS-CoV-2 as **"droplet/airborne"** (NHS-England 2022). (NB. A full discussion of this subject is provided in Part 2.)

19. The role of respiratory droplets and aerosols in the transmission of SARS-CoV-2 is illustrated in Figure 1, which shows the larger exhaled droplets (>100µm diameter) rapidly falling to the ground, while all smaller particles become aerosols which float in the air and can be inhaled (reproduced from (Wang et al. 2021a)).

**** and other respiratory virus infections can be transmitted**

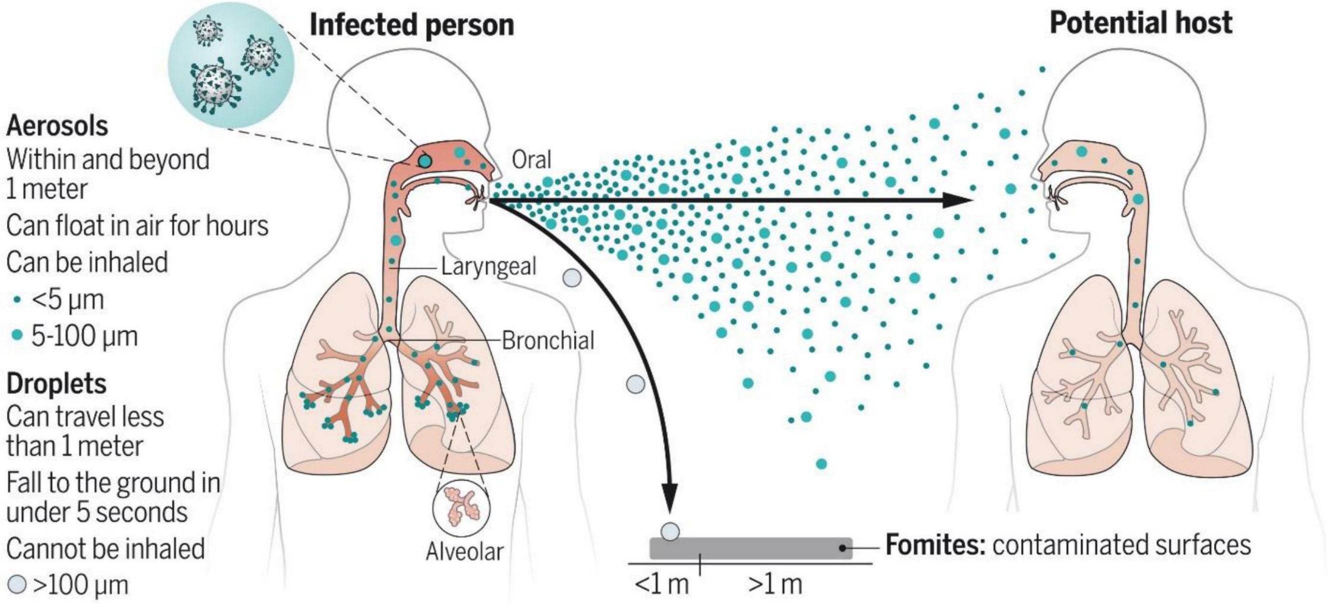


Figure 1. Phases involved in transmission of respiratory viruses. Virus-laden aerosols (<100µm) are first generated by an infected individual through expiratory activities, through which they are exhaled and transported in the environment. They may be inhaled by a potential host to initiate a new infection, provided that they remain infectious. In contrast to larger droplets (>100 µm), aerosols can linger in air for hours and travel beyond 1 to 2 m from the infected individual who exhales them, causing new infections at both short and long ranges (Wang et al. 2021a).

20. For viral infection to be transmitted by the respiratory route, infectious material must first be exhaled by an infectious person, and transmitted through the air, before being inhaled by a susceptible person and then infecting the cells in the lining of their nose, throat or lungs. The cells in these tissues contain the ACE2 and sialic acid receptors that mediate the transmission of Covid-19 and influenza, and which act as targets onto which the virus particles bind. ACE2 and sialic acid receptors are also present on the surface of the eyes, and it has been hypothesized that large respiratory droplets (i.e., >100µm diameter) and aerosols impacting on the eyes could facilitate the transmission of infection (Grajewski et al. 2021; PIP-Team 2011b), although the extent to which this occurs is not known. Alternatively, exhaled infectious material can contaminate surfaces, hands or the face, and be transmitted by direct or indirect touch rather than inhalation. However, the precise mechanisms involved in the transport of virus particles from the hands to the ACE2 and sialic acid receptors in the nose, throat and eyes are poorly understood, and doubt has been expressed about the extent to which this happens (PIP-Team 2011a). Therefore, understanding each step in the transmission process is essential when developing effective IPC interventions aimed at preventing the transmission of respiratory viral infections.

21. Faecal-oral transmission refers to the ingestion of virus in faecal matter, either directly via unwashed contaminated hands, or alternatively via contaminated food and drink. SARS-CoV-2 genetic material can survive in faeces and is often recovered from the faecal waste of humans. Although, SARS-CoV-2 in faeces is potentially infectious (Dergham et al. 2021), and has been shown to infect animals or human cells in the laboratory (Jeong et al. 2020), there is very limited real-world evidence to assess how often faecal-oral transmission occurs. Indeed, a systematic review published in 2023 (Termansen & Frische 2023) could only find three epidemiological studies addressing this question. This review concluded that, although faecal SARS-CoV-2 is

infectious, there was ***“no strong direct evidence for faecal-oral transmission of SARS-CoV-2 between humans”***. This was because there was ***“only limited circumstantial evidence of documented faecal-oral transmission between humans”***. However, the authors of the study did not dismiss the possibility that faecal-oral transmission might be occurring.

22. Other routes by which infection can be spread include blood-borne, sexual and vector-borne (insect or arthropod mediated) transmission. Although these routes could contribute to future pandemics and epidemics, and have IPC implications for hospitals (e.g., HIV transmission by needlestick injuries), SARS-CoV-2 is rarely, if ever, transmitted by these routes (Dangalle 2021; Tur-Kaspa et al. 2021). Consequently, these routes of transmission are not featured in this report.

Respiratory transmission

23. In this section, we focus on the transmission of viral infections through the air, also known as respiratory transmission. In particular, we review the physical science associated with the exhalation, inhalation and transport of respiratory particles in air. Key issues such as particle size, viral load, infectious dose, and asymptomatic transmission are also discussed.

Exhalation

Key findings:

- People exhale many thousands of tiny respiratory particles every minute.
- Compared with breathing, the number of particles exhaled greatly increases as people talk loudly, sing, cough or sneeze.
- The exhaled respiratory particles have a wide range of sizes, with most being very small, less than 20µm diameter, while a few can be greater than 100µm.
- Due to evaporation, once exhaled, respiratory particles rapidly shrink in size to about a third of their original diameter.
- The largest particles, those greater than about 100µm diameter, behave ballistically (like a ball being thrown) and quickly fall to the ground, but most particles less than 100µm rapidly evaporate to become small aerosol particles of various sizes that can float in air.
- The size of the exhaled particles reflects the location in the body where they are formed, with those less than 5µm diameter most likely to originate deep in the lungs or at the vocal cords, whereas the largest respiratory particles tend to be generated in the mouth.
- The viruses contained in the exhaled aerosols tend to originate at the site in the body where the aerosol particle is generated.
- For SARS-CoV-2 and influenza, most of the exhaled viral load tends to be found in smallest aerosol particles less than 5µm diameter.
- Respiratory particles of all sizes are exhaled in a cone-shaped plume (or cloud), which is turbulent and sucks in air as it expands.
- During coughing and sneezing, quite large particles can be projected many metres through the air (far further than 2 metres), whereas the largest particles, >100µm, rapidly fall out of the exhaled cloud to the floor.

24. Respiratory particles exhaled by a person can range from 0.01 to 1000µm in diameter (Bake et al. 2019), depending on where the particle is generated (i.e., lungs, vocal chords, throat or mouth), the type of activity (i.e., breathing, talking, singing, coughing or sneezing), and the surface tension of the fluid in the lungs (Bake et al. 2019; Stadnytskyi et al. 2021). The physiological processes involved are complex, with particles of different sizes produced in different parts of the body, as illustrated in Figure 2 (reproduced from (Stadnytskyi et al. 2021)).

25. Although there is considerable variation between individuals, in simple terms the smallest particles (0.01 to 2µm) tend to originate deep in the small airways of the lungs, while the largest (which range in size, but can be >100µm diameter) are generated in the mouth. However, respiratory particles of various sizes are also produced by the vocal chords and in the larger airways of the lungs (Morawska et al. 2009; Stadnytskyi et al. 2021). The larger particles that are generated in the mouth contain mostly saliva, while those produced deeper in the lungs contain respiratory tract lining fluid (RTLF), which contains surfactants that reduce surface tension and enables small aerosol particles to form. Viruses, bacteria and other microbes can become suspended in these respiratory particles, with the microbial constitution of particles reflecting the site of origin (Stadnytskyi et al. 2021). This means that smaller respiratory particles are more likely to contain viruses and bacteria that originated deeper in the lungs, while those generated in the mouth will reflect the microbes found there.

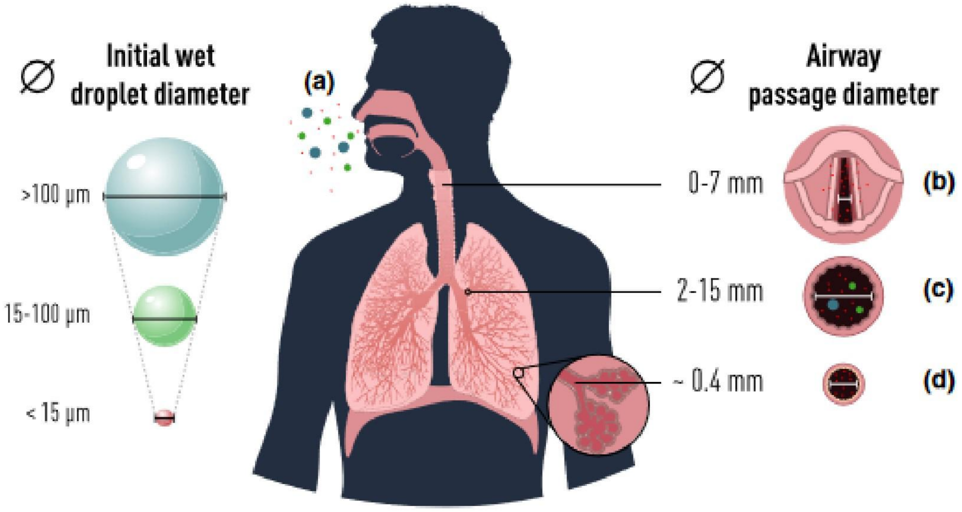


Figure 2. Respiratory particles emitted during exhalation, vocalizing, coughing or sneezing span a broad range of sizes that depend on the site of origin. Particles are colour-coded according to their initial, fully hydrated diameter: red (<15µm); green (15-100µm); and blue (>100µm). Once airborne, they shrink about threefold. (a) Largest particles are generated during vocalization near the front of the oral cavity, where airflow is modulated by varying gaps between lips, tongue, and teeth. (b) Small particles are generated by the vocal folds when vocalizing. (c) Rapid airflow through the central and upper airways during coughing, sneezing or sudden exhalation can produce a wide size distribution of particles. (d) Transient closure of the distal airways is assumed to be responsible for the generation of smallest aerosol particles (Stadnytskyi et al. 2021).

26. With reference to Covid-19 and influenza, the location at which respiratory particles are generated in the human body is an issue of great importance. This is because the microbes in respiratory particles reflect the site of origin. Several studies involving influenza patients have shown the majority of exhaled virus particles are found in the small respiratory particles <5µm diameter (Bischoff et al. 2013; Coleman & Sigler 2020; Lindsley et al. 2010b; Yan et al. 2018). Similar results have been observed for Covid-positive subjects (Alsved et al. 2023a; Coleman et al. 2022; Jaumdally et al. 2024; Tan et al. 2023). This suggests that virus particles exhaled by people infected with SARS-CoV-2 and influenza are more likely to be found in the smallest particles that

do not originate in the mouth, but rather are generated deeper in the lungs or by the vocal chords (Morawska et al. 2009; Stadnytskyi et al. 2021).

27. During normal breathing the smallest airways in the lungs open and close during inhalation and exhalation. This causes thin films of RTLF to form which can burst, forming numerous tiny aerosol particles that are then exhaled (Stadnytskyi et al. 2021). The small particles generated by this mechanism are generally <4μm in diameter (Bake et al. 2019), but are often smaller in the size range 0.01 to 2μm diameter (Holmgren et al. 2010). However, during speaking, shouting or singing the vocal chords are activated and the vibrations associated with these disrupt the mucus layers covering the vocal folds so that large numbers of small particles are generated, mostly in the size range 1 to 5μm (Stadnytskyi et al. 2021), which greatly increase in number with loudness (Alsved et al. 2020). In addition, during vocalisation larger particles are generated near the front of the mouth by varying the gaps between lips, tongue, and teeth (Stadnytskyi et al. 2021). These vary in size, with some being >100μm in diameter (see Figure 2).

28. When people cough or sneeze, in addition to all the particle-generating mechanisms described above, an additional mechanism comes into play which involves the mucus lining of the large airways in the lungs. During sneezing and coughing, air is forced out the lungs at high velocity. This causes turbulence in the larger airways, disrupting the RTLF and generating large numbers of particles that range in size from <1 to >100μm in diameter (Stadnytskyi et al. 2021). So, with coughing or sneezing, huge numbers (many thousands (Dhand & Li 2020)) of respiratory particles of various sizes are violently expelled into the air, as illustrated in Figure 3 which shows a sneeze. However, the vast majority of these particles are very small, with most being <20μm (Basu 2021).

Figure 3. Photograph of a sneeze, revealing the cone-shaped exhalation plume of salivary droplets and aerosol particles produced from the mouth [By James Gathany - CDC Public Health Image library ID 11162, Public Domain, available from: https://commons.wikimedia.org/w/index.php?curid=6701700]

29. To put all this into context, 0.01μm is about the same size as the diameter of a SARS-CoV-2 virus itself. So, if a 0.01μm virus was the size of a football, then a 1μm respiratory particle would be larger than a hot air balloon, which means that potentially many thousands of viruses could be

contained in a single 1µm respiratory particle. Such particles are tiny, and as such can only be observed using a microscope. By comparison, larger respiratory particles are visible with the naked eye. For example, 50µm particles are approximately the same diameter of a human hair, while the very largest at 1000µm, or one millimetre (1mm), are approximately the same diameter of a grain of coarse sand.

30. A further important point is that no matter their size, all respiratory particles comprise mainly of water, because they are formed in the lungs, throat and mouth, which is a very damp environment. This means that as soon as the particles exit the mouth or nose and enter drier air, they immediately start to lose water due to evaporation and dramatically shrink in size to about a third of their original diameter (Basu 2021). This process is very rapid, with particles less than about 80µm evaporating within about one second (Wei & Li 2015). Indeed, under normal room conditions, all exhaled respiratory particles <100µm in diameter will evaporate to about a third (actually 20 to 34% (Basu 2021)) of their original size before they can touch the floor. This means that due to evaporation, all exhaled respiratory particles <100µm in diameter will rapidly become much smaller particles (of various sizes) that can be suspended in the air and float around. Given that vast majority of respiratory particles produced during speaking and coughing are much smaller than this 100µm threshold (Beggs 2020)*, it means that after evaporation the respiratory particles found in room air tend to be <20µm (Basu 2021), with most in the range 1 to 10µm in diameter. Particles of this size can easily remain suspended in the air for many minutes, or even hours (see paragraphs 58 - 59 for details).

31. By comparison, respiratory particles that are >100µm when they are exhaled are so large that they cannot evaporate before they hit the floor. Because of their large size, they are heavy, which means that they possess considerable momentum, and are therefore not affected by air room currents. Consequently, they behave ballistically (i.e., like a stone being thrown) and rapidly fall to the ground within 2 metres of the source (Wei & Li 2015). This makes them very difficult (perhaps impossible) to inhale (Wang et al. 2021a), because from the moment they leave the mouth they are rapidly descending towards the floor, away from the breathing zone of other people.

32. So far, we have used the term 'respiratory particle' rather than 'droplet'. This has been done deliberately because of the confusion that has historically been associated with the term 'droplet', and which prior to (and during) the Covid-19 pandemic led to serious errors in the scientific literature (see paragraphs 113 to 176). However, in order to aid understanding of key concepts in this report, we now need to make a distinction between 'aerosol particles' and 'droplets', in line with current (consensus) scientific thinking that emerged during the Covid-19 pandemic (Morawska et al. 2023; Tang et al. 2021a), and which corrects many of the errors in the historical literature.

33. An aerosol is widely defined by physical scientists to be a suspension of solid or liquid particles in air. By 'suspension', we mean a mixture of small particles (correctly termed **'aerosol particles'**) and air. The key characteristics of an aerosol are that: (i) the particles are so light that they float about in the air; and (ii) the particles travel wherever the air currents take them. Having said this, if the air currents are not strong enough, the larger aerosol particles will gradually (over minutes or hours, depending on their size) settle out due to gravity. Droplets, by contrast, are specifically liquid particles, which are kept together by surface tension, and can be as large as raindrops, several millimetres across. Although technically some droplets can be small enough to remain suspended in the air (i.e., microdroplets), in the context of infectious disease transmission, the term **'droplet'** is increasingly being used to describe those respiratory particles >100µm in

diameter (Chen et al. 2021a; Prather et al. 2020a; SAGE-EMG 2021; Tang et al. 2021a; Wang et al. 2021a), which cannot full evaporate before that hit the ground and therefore behave ballistically. Therefore, in line with state-of-the-art physical scientific knowledge (Morawska et al. 2023; SAGE-EMG 2021; Tang et al. 2021a), we will hereafter refer to exhaled respiratory particles <100µm diameter as 'aerosol particles', and those >100µm will be termed 'droplets'. It is worth noting that this is not a hard cut-off – if air currents are strong enough, some larger particles do not behave ballistically.

34. The word "droplet" is used by physical scientists to describe the physical properties of particles made largely of water or other fluids that behave ballistically when projected. **As such, use of this terminology this does not support the specific route of transmission known as "droplet transmission"** often cited in the medical literature, where it is assumed that pathogen species are transmitted in so-called 'droplets' larger than 5µm, which can travel no further than about 1.5 metres (see part 2 for further details). Particles of this size actually behave as aerosols, rather than droplets, which means that they can remain suspended in air and can travel far further than 2 metres. In fact, the threshold of 5µm diameter, which historically has been widely used in the medical literature (e.g., (Ayliffe et al. 1982; Tabatabaeizadeh 2021; WHO 2014; Zhou et al. 2018)) to distinguish between 'droplets' and so-called 'droplet nuclei' has no basis in physics and is completely arbitrary (see part 2 for details).

35. Figure 3 demonstrates the wide range of particles produced by a sneeze. From this, it can be seen that a cloud containing a very large number of fine **aerosol particles** is produced, as well as relatively few larger **droplets**, which quickly fall out of the cloud to the ground. The aerosol cloud itself is turbulent, with edges that swirl, which means that as it travels, fine aerosol particles are continually being dispersed into the air from the edges of the cloud, which is sometime called an exhalation plume. The fluid mechanics of the gas cloud are such that it increases the distance travelled by the aerosol particles, which in extreme cases can travel up to 8m (Bourouiba 2020; Bourouiba et al. 2014).

36. Although the number of respiratory particles exhaled varies greatly between individuals, as a general rule, the numbers produced depend very much on the nature and loudness of any vocalisation. For example, Alsved et al. (Alsved et al. 2020) found that the median emission rates of inhalable aerosol particles in the range 0.5 - 10µm were 135 particles per second for breathing; 270 particles/s for normal talking; 570 particles/s for loud talking; 690 particles/s for normal singing; 980 particles/s for loud singing; and 1480 particles/s for loud singing with exaggerated diction. Other researchers have reported similar findings (Asadi et al. 2019; Coleman et al. 2022; Gregson et al. 2020). As such, this indicates that large numbers of respiratory aerosols are continually liberated into room air every second, particularly when voices are raised. Vocalisation and loudness also appear to influence the amount of SARS-CoV-2 virus that is exhaled when people are infected (Alsved et al. 2023a), and this is one of the sources of variation between people and settings that contributes to the superspreading phenomenon (see paragraphs 106 to 112 for details).

37. Paradoxically, while the vast majority of respiratory particles are <10µm diameter, only about 1% of the exhaled respiratory fluid by volume is contained in these small aerosol particles (PIP-Team 2011b; Weber & Stilianakis 2008). Historically, this led many to conclude, wrongly, that the vast majority of exhaled viruses would be contained in large droplets, which were assumed to travel no further than about 1.5m (PIP-Team 2011b; Weber & Stilianakis 2008). However, in recent years this assumption has been shown to be incorrect, with numerous studies involving SARS-CoV-2 (Alsved et al. 2023a; Coleman et al. 2022; Jaumdally et al. 2024; Tan et al. 2023) and

influenza (Bischoff et al. 2013; Coleman & Sigler 2020; Lindsley et al. 2010b; Yan et al. 2018) patients showing that the majority of exhaled viruses are found in fine aerosol particles <5μm diameter.

Virus shedding and the presence of symptoms

Key findings:

- People infected with SARS-CoV-2 can exhale over a million virus particles per hour into the air, but this varies a great deal from person to person.
- Viral load in Covid-19 peaks around the time of symptom onset, so even if an infected person is not coughing, they can still be highly infectious when just breathing and talking.
- The viral load exhaled greatly increases with more and louder vocalisation, and so those shouting and singing are especially prone to transmit airborne infection.
- For SARS-CoV-2 and influenza, the vast majority of the exhaled viral RNA is found in smallest aerosol particles less than 5μm in diameter.
- In controlled experiments, SARS-CoV-2 in aerosol particles can remain viable for over an hour, and able to cause infection.
- Although some researchers have failed to culture live SARS-CoV-2 virus from the air near Covid-19 patients, others have, suggesting that the virus can remain viable when exhaled in respiratory aerosols. Evidence from animal studies involving inoculated ferrets corroborates this opinion and strongly indicates that both SARS-CoV-2 and influenza can remain viable in respiratory aerosols and cause infection.
- Infected people can shed SARS-CoV-2 even in the absence of symptoms, whether they are in the presymptomatic phase of illness or whether they have true asymptomatic infection.

38. Like many other respiratory viruses, once a person becomes infected with SARS-CoV-2 it takes several days before symptoms start to appear. It is during this pre-symptomatic period, when the virus is incubating, that individuals are the most contagious, with the virus able to spread 2 to 3 days before any symptoms develop (He et al. 2020). Although this is broadly true for all strains of SARS-CoV-2, there is some variation between strains. The incubation period for the original (Wuhan) strain has been estimated to be between 4.6 and 6.4 days, whereas in comparison the Delta and Omicron BA.1 strains have shorter incubation periods, estimated to be approximately 3.7–4 days and 3–3.4 days for Delta and Omicron BA.1, respectively (Puhach et al. 2023).

39. Symptoms and the degree to which a person is infectious are both related to the viral load in the body. The viral load in the body changes with time and varies depending on the sampling site and method (i.e., throat swabs, nasal swabs, sputum samples, etc.) (Pan et al. 2020). It also varies from individual to individual. Viral load is generally measured in RNA copies per millilitre (copies/mL or RNA/mL) and can range from a several hundred to many millions of RNA copies

per mL, with most samples ranging from tens of thousands to hundreds of thousands (e.g., a median of $7{\cdot}99 \times 10^4$ for throat samples and $7{\cdot}52 \times 10^5$ for sputum samples (Pan et al. 2020).) However, infectious individuals typically have viral loads of more than a million ($>10^6$) RNA copies per mL (Puhach et al. 2023).

40. The relationship between viral load, symptoms and infectivity is illustrated in Figure 4, which is reproduced from Puhach et al. (Puhach et al. 2023). This shows how the viral load changes with time in patients infected with the original (Wuhan) strain of SARS-CoV-2. From this, it can be seen that a steep rise in viral load occurs before symptoms appear, during which time the person is highly infectious. This highly infectious state peaks with the onset of Covid-19 symptoms and then gradually diminishes as the infection wanes, with the person generally becoming non-infectious after about 10 to 12 days.

41. While the virus kinetics shown in Figure 4 are typical for people who become ill, sometimes, individuals can be infected with Covid-19 and never develop any symptoms at all. Such people are termed ‘**asymptomatic**’. However, this does not mean that asymptomatic people cannot be infectious. Indeed, it is now known that much SARS-CoV-2 infection is transmitted by people who are either asymptomatic or **pre-symptomatic** (Oran & Topol 2020; Oran & Topol 2021; Sah et al. 2021). Infected individuals who display minimal or very minor symptoms are often referred to as being ‘paucisymptomatic’. This topic is covered further in the next section, paragraphs 48 to 53.

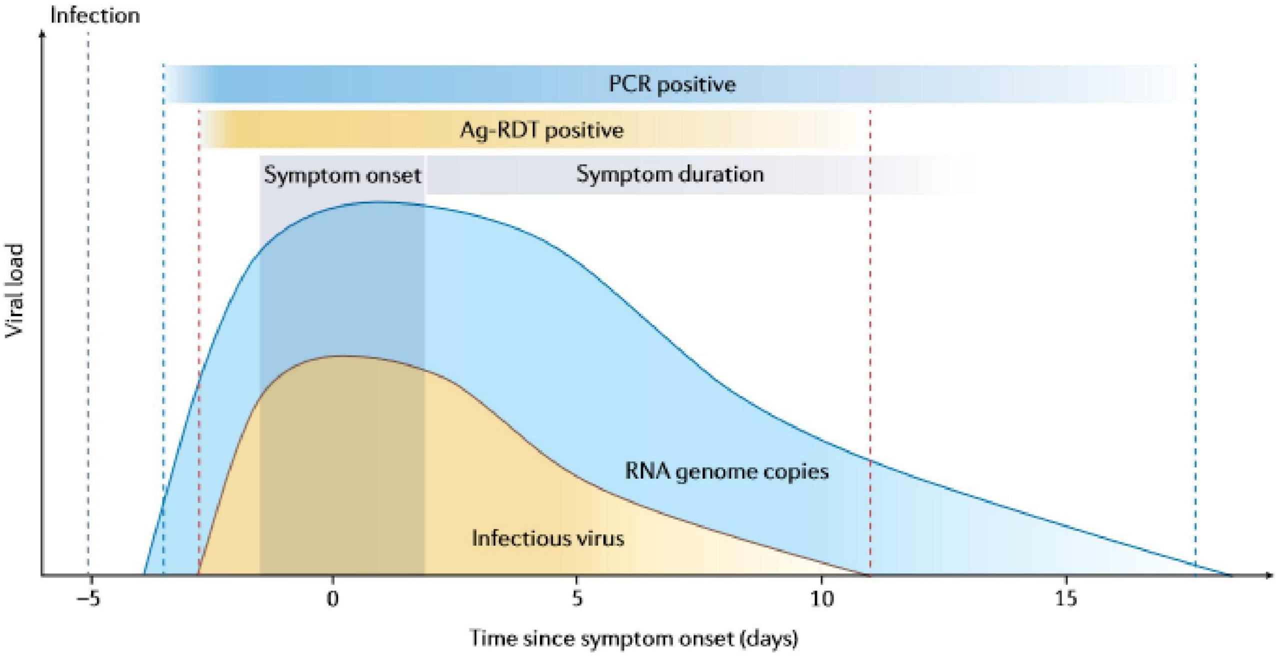


Figure 4. Trends of RNA viral loads and infectious virus for the original strain of SARS-CoV-2 in patients with mild-to-moderate disease (Puhach et al. 2023).

42. Historically, much attention in public health campaigns has been given to coughs and sneezes, exemplified by the famous saying *“coughs and sneezes spread diseases”* originating in the 1918 influenza pandemic. The respiratory particles generated by everyday activities such as talking and breathing have, by contrast, have been largely ignored. These however, can be produced in considerable numbers, with for example, 85-691 and 120–1,380 particles per second exhaled

during breathing and talking, respectively (Alsved et al. 2020). Although not visible to the naked eye, these aerosol particles are exhaled in a turbulent cloud (or plume) that rapidly diffuse into the room air, as illustrated in Figure 5.

Figure 5. Schlieren image showing the interaction of two exhaled airflows between two people (reproduced from https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0021392, CC BY 4.0, https://commons.wikimedia.org/w/index.php?curid=90043870 (Tang et al. 2011))

43. Several studies have demonstrated that the majority of SARS-CoV-2 RNA that is exhaled is found in small aerosol particles <5μm in diameter (Alsved et al. 2023a; Coleman et al. 2022; Jaumdally et al. 2024; Tan et al. 2023). For example, Alsved et al. (Alsved et al. 2023a) found 90% of the SARS-CoV-2 RNA exhaled during breathing, talking and singing to be in particles <4.5μm. Similar, findings were observed by Coleman et al. (Coleman et al. 2022), who observed that 94% of SARS-CoV-2 RNA copies were emitted by talking and singing, with 85% contained in fine aerosol particles <5μm in diameter. Furthermore, live virus has also been cultured from aerosol particles <5μm produced by Covid-19 patients (Alsved et al. 2023b; Jaumdally et al. 2024; Lednicky et al. 2020), reinforcing the consensus that it is the very small aerosol particles that contain most virus. When breathing, these fine particles are generated in the small airways of the lungs (Bake et al. 2019; Stadnytskyi et al. 2021). However, their numbers greatly increase during talking and singing (Alsved et al. 2023a), because the vocal cords also produce aerosol particles in this size range (Stadnytskyi et al. 2021). As a result, in comparison to breathing, the number of virus particles exhaled greatly increase with vocalisation as illustrated in Figure 6a, which shows the huge increase that occurs when an infected person sings and, to a lesser extent, talks. Figure 6b also shows how the number of virus particles produced decrease as infection progresses.

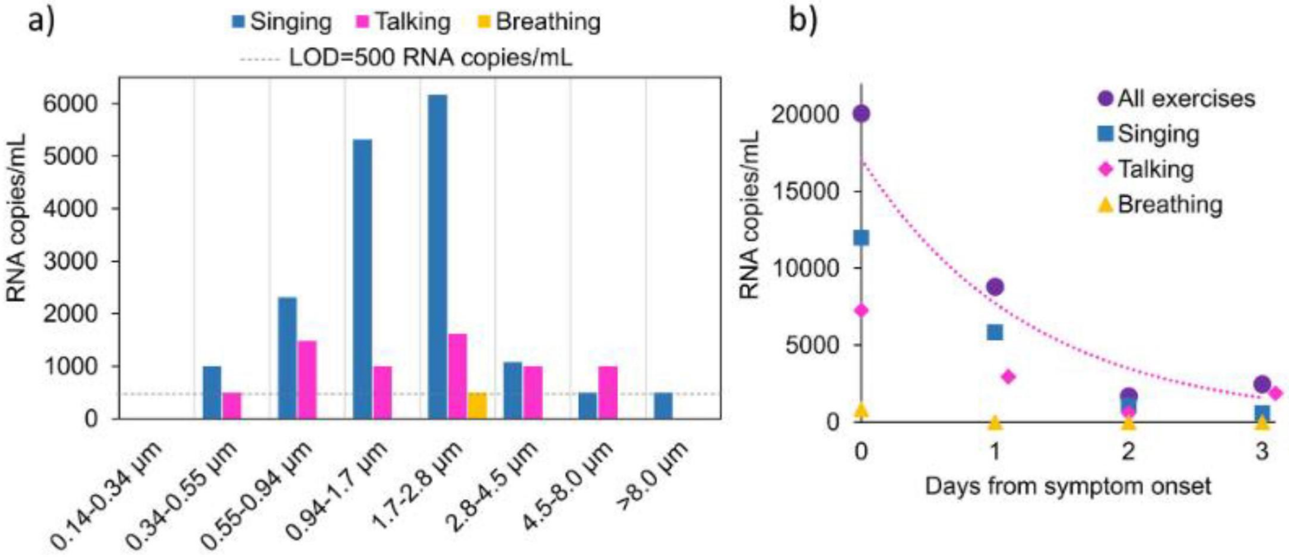


Figure 6. Virus exhalation when singing, talking and breathing. (a) SARS-CoV-2 RNA concentrations from each exercise according to particle size. The dashed line indicates the limit of detection (LOD) concentration for one sample. (b) The concentrations of SARS-CoV-2 RNA on the day of symptom onset (day 0) and the following three days (all particle size fractions added together). An exponential trend line was fitted to the 'All exercises' data series (Alsved et al. 2023a).

44. These observations are supported by the findings of a laboratory study involving cynomolgus monkeys infected with SARS-CoV-2 (Zhang et al. 2021), which found that when anesthetized (with the monkeys breathing slowly through their nostrils), each monkey exhaled on average 503 virus particles per minute (two days post-infection), with the majority of viruses found in small aerosol particles <4.5µm diameter. The virus particles exhaled, peaked two days after infection and ranged from 11,578 to 28,336 virus (RNA) copies shed during a 40-minute period. While these numbers are large, because the lung capacity of the monkeys is much smaller than that of humans, they probably represent an underestimate of the number of virus particles exhaled by people infected with SARS-CoV-2 (Zhang et al. 2021). Indeed, Ma et al. (Ma et al. 2021) found that humans infected with SARS-CoV-2 exhaled in the region of 1.03 x 10^5 to 2.25 x 10^7 viruses per hour, confirming that large quantities of viral material can be shed into room air by infectious individuals.

45. While the evidence presented above strongly suggests that: (i) large quantities of genetic material are exhaled by Covid-19 patients; and: (ii) that the bulk of the exhaled viral material resides in the smaller aerosol particles, **uncertainty still remains about the ability of the virus to cause infection when exhaled in aerosols.** This is because many studies simply recovered RNA and made no attempt to culture the virus. Others have recovered RNA from the air but failed to culture any virus (Johnson et al. 2022; Otter et al. 2023; Zhou et al. 2021), suggesting that the aerosolised RNA might not be capable of causing infection. However, failure to culture virus from the air, might be due to the sampling method used, rather than the virus being non-viable. Viruses are difficult to culture from the air, because they are easily damaged by the shear forces experienced during the sampling process, which can render them non-viable (Singanayagam et al. 2020). By contrast, a number of studies that have successfully cultured viable virus from the air exhaled by (or close to) Covid-19 (Alsved et al. 2023b; Jaumdally et al. 2024; Lednicky et al. 2020) and influenza

(Lednicky & Loeb 2013; Yan et al. 2018) patients. So, there is evidence that viable virus can be recovered from exhaled aerosols. Furthermore, numerous laboratory studies involving levitated aerosols have shown that viable SARS-CoV-2 can survive in small aerosols (about 2µm diameter) for more than an hour (Dabisch et al. 2020; Fears et al. 2020; Schuit et al. 2020; Smither et al. 2020; Van Doremalen et al. 2020b). So, there is moderate evidence that viable virus material can survive in respiratory aerosol particles. This is clearly the opinion of the CDC who state, ***"COVID-19 spreads when an infected person breathes out droplets and very small particles that contain the virus, (which) other people can breathe in …"*** (CDC 2024a).

46. Further evidence supporting the transmission of respiratory viruses in aerosols comes from studies involving ferrets, which are often used as a surrogate for human transmission. Zhou et al. (Zhou et al. 2018) recovered influenza RNA form ***"droplets (15.3–5µm) as well as fine droplet nuclei (5–1.5µm)"*** exhaled by ferrets. Similarly, Gustin et al. (Gustin et al. 2011), who also recovered viable influenza virus, found ***"peak virus in particles >4.7µm in size (40–1,180 pfu viable virus; 45–1,678 RNA copies) (more) than in aerosols 0.65–4.7µm in size, which peaked at 7–10 pfu viable virus and 14–41 RNA copies"***. As such, both research teams found that most of the influenza virus exhaled by the ferrets was in respiratory particles that were technically aerosols, and which can be suspended in air and inhaled, as illustrated in Figure 1. **However, because Zhou et al. erroneous used the >5µm criterion to define droplets, they reported that the bulk of the viral material was found in droplets, which is incorrect, because all the measured particles sizes were actually aerosols, albeit of various sizes.**

47. Aerosol transmission of influenza (A/H1N1), SARS-CoV-2 and SARS-CoV between ferrets was conclusively demonstrated, in an experiment reported by Kutter et al. (Kutter et al. 2021), in which inoculated ferrets, located in a lower chamber, infected recipient ferrets in an upper chamber through the air. The experiment was cleverly designed with the air between the ferrets traveling uphill for more than one metre in a pipe, which had several bends in it. This ensured that large droplets >100µm could not travel between the two enclosures housing the ferrets, thus ensuring that the infectious particles reaching the ferrets in the upper chamber must be inhalable aerosols of various sizes. In the experiment, which involved sets of paired ferrets: influenza transmission occurred in four out of four (100%) pairs; SARS-CoV-2 transmission occurred in two out of four (50%) pairs; and SARS-CoV transmission occurred in four out of four (100%) pairs. Kutter et al's experiment mirrored a much earlier experiment with a similar design by Andrewes and Glover (Andrewes & Glover 1941), which similarly found that ferrets inoculated with influenza could infect other ferrets with exhaled particles that travelled uphill in air. **Collectively, this strongly suggests that the route of transmission is likely the same for SARS-CoV-2, SARS-CoV and influenza, and that in both experiments the aerosolised virus was viable and able to cause infection.**

Asymptomatic transmission

Key findings:

- A third to half of all Covid-19 cases are asymptomatic, in which people have no or very few symptoms.
- Although asymptomatic transmission of SARS-CoV-2 is a widespread phenomenon, early in the Covid-19 pandemic it was not known to what extent it occurred. SAGE regularly reported on the gradually strengthening evidence base and by September 2020 confirmed definitively that it was occurring.
- Asymptomatic transmission of SARS-CoV-2 accounts for many Covid-19 infections acquired in hospitals.
- There is some evidence that influenza can also be transmitted by asymptomatic people who are infectious.

48. Far from being a rare occurrence, asymptomatic Covid-19 infection is commonplace (Gandhi et al. 2020; Hu et al. 2020), with about a third to half of cases thought to involve asymptomatic transmission (Johansson et al. 2021; Shang et al. 2022), particularly in children and young people. For example, in 2023 a comprehensive review with meta-analysis (Wang et al. 2023) found that about 44% of Covid-19 cases were reported as asymptomatic throughout the course of infection, with highest rates occurring in children, teenagers and young adults under 30 years of age. By comparison asymptomatic carriage was lower amongst middle aged people (about 20 to 25%) and lower still in elderly individuals (about 10%).

49. However, asymptomatic infection does not necessarily lead to asymptomatic transmission and it is important to distinguish between the two (DHSC 2023). Early in the Covid-19 pandemic it was recognised that asymptomatic transmission of SARS-CoV-2 might be problematic, with the minutes of the fourth SAGE meeting (4th February 2020) stating: ***"Asymptomatic transmission cannot be ruled out and transmission from mildly symptomatic individuals is likely."*** (SAGE 2020a). This reflects the uncertainty that existed at the time regarding the ability of asymptomatic and paucisymptomatic individuals to infect others. Prior to the pandemic there was limited evidence that influenza could be transmitted by asymptomatic individuals (Ip et al. 2017; Leung et al. 2015), but this was disputed by others (Patrozou & Mermel 2009) (see paragraph 53). There was also evidence that HCWs could be infected with the SARS coronavirus while remaining asymptomatic (Wilder-Smith et al. 2005), but evidence of onwards transmission from those with the original SARS coronavirus was lacking. However, over time, evidence emerged that asymptomatic SARS-CoV-2 transmission was likely occurring (Bai et al. 2020; Ladhani et al. 2020). This was definitely confirmed by SAGE on the 10th September 2020 (SAGE 2020b), although the extent to which asymptomatic and pre-symptomatic individuals contributed to transmission remained unclear, as highlighted in a BMJ editorial published 21st December 2020 (Pollock & Lancaster 2020). Notwithstanding this, although asymptomatic individuals might be less infectious than those with symptoms, a consensus emerged that they nonetheless posed a substantial public health risk (DHSC 2023; Rasmussen & Popescu 2021). (NB. The author has limited expertise in the field of asymptomatic transmission of viral infections, and so readers are

directed to the UK Covid-19 Inquiry's clinical expert report by Professor Dinah Gould, Dr Ben Warne, and Dr Gee Yen Shin for a more comprehensive discussion of this subject.)

50. In the NHS, a surveillance study involving over 1,000 people, undertaken in April 2020 in a large UK teaching hospital, it was found that 3% of HCWs who appeared asymptomatic actually tested positive for SARS-CoV-2 (Rivett et al. 2020). As such, the potential risk posed by Covid-positive asymptomatic HCWs in the NHS was recognised relatively early in 2020. SARS-CoV-2 transmission from asymptomatic patients was also recognised as a problem; something which was highlighted by Illingworth et al. (Illingworth et al. 2021) and Cooper et al. (Cooper et al. 2021) in August and November 2021.

51. Given that many people infected with SARS-CoV-2 display little or no symptoms, it is likely that aerosols generated by such people during breathing and talking, but not coughing or sneezing, significantly contributed to the spread of the disease during the pandemic. This includes patients and HCWs in hospitals, as highlighted in Cooper and colleagues' surveillance study of 145 English NHS acute hospital trusts (Cooper et al. 2021; Cooper et al. 2023).

52. Even when fully vaccinated, people infected with Omicron exhale similar amounts of SARS-CoV-2 RNA in aerosols to those infected with the pre-Omicron variants (Tan et al. 2023). Also, they appear to exhibit persistent aerosol shedding beyond seven days after disease onset (despite being fully vaccinated and largely being asymptomatic), which is something that may contribute to Omicron's greater transmissibility.

53. Most cases of seasonal influenza are thought to be asymptomatic (Hayward et al. 2014). There also is evidence that asymptomatic transmission of influenza can also occur (Ip et al. 2017; Leung et al. 2015; Montgomery et al. 2023; Tsang et al. 2023), although this is disputed (Patrozou & Mermel 2009), and the extent to which this happens is not fully understood. Published studies on the subject suggest that considerable variation exists regarding this phenomenon. However, a comprehensive systematic review (with meta-analysis) published in 2015 indicated that this variability appears to be primarily due to different methodologies being used in the various studies, and that on average about 16% of influenza cases were asymptomatic (Leung et al. 2015), which is considerably less than that reported by Hayward et al. (Hayward et al. 2014). As such, there was some evidence in the public domain supporting the asymptomatic transmission of influenza before the onset of the Covid-19 pandemic. However, relatively little is known about the risks posed by asymptomatic carriers of influenza, although it has been observed that people with no or minimal symptoms appear to shed less virus than those who exhibit symptoms (Ip et al. 2017). One factor counteracting this lower infectiousness is that people with few or no symptoms often have much higher contact rates because they do not feel ill and therefore don't stay at home (Van Kerckhove et al. 2013).

How infectious particles move through the air

Key findings:

- Exhaled respiratory droplets >100µm behave ballistically (like a stone being thrown) and fall rapidly to the floor. They rarely travel further than 2 meters.
- Smaller respiratory particles <100µm rapidly shrink in size due to evaporation and become tiny aerosol particles which can float in air.
- These small aerosol particles take many minutes (even hours) to settle out of the air and therefore can be transported long distances around rooms by air currents.
- Thermal plumes, which are upward flowing currents of air that surround all people, are particularly important, because they transport the tiny aerosols toward the ceiling and then push them around the room.
- Thermal plumes, which are upward flowing currents of air that surround all people, are particularly important, because they can transport even quite large aerosols of 20µm (in theory even 30µm) toward the ceiling and then push them around the room, much further than 2 metres.

54. In this section the physical science associated with the transport of infectious particles through the air is explained. While primarily focused on SARS-CoV-2, the discussion here is equally applicable to other respiratory viruses, such as influenza, as well as to TB. Historically, this subject has been largely neglected by the mainstream IPC community, with the result many misconceptions and erroneous ‘facts’ have crept into the scientific literature (Tang et al. 2021a; Tang et al. 2021b), which during the Covid-19 pandemic culminated in the WHO and the Centers for Disease Control and Prevention (CDC) denying in 2020 that SARS-CoV-2 could be transmitted by the airborne route (Lewis 2022; Morawska et al. 2023) (see Part 2). Therefore, in order to learn lessons from the Covid-19 pandemic, it is important to understand how infectious respiratory particles behave once they have been exhaled into room air.

55. Also, because the air is the place where the greatest attrition (removal or inactivation) of virus particles can take place, this affords the opportunity for NPIs, such as improved room ventilation and air cleaning, to reduce the viral load and thus mitigate the risk of transmission. Therefore, it is important to understand how respiratory particles behave in the air so that interventions can be optimised.

56. For Covid-19 transmission to take place, exhalation of infectious respiratory particles must be followed by movement of those particles from the infected person to one or more susceptible people. While this might involve contact transmission via hands, it is now generally agreed that for SARS-CoV-2 and influenza most of the transmission involves respiratory particles traversing through the air. In other words, it involves either large droplets >100µm in diameter that behave ballistically, rapidly falling to the ground, or smaller aerosol particles, which tend to float about on room air currents (convection currents).

57. After exhalation, respiratory particles undergo rapid evaporation (Wei & Li 2015; Xie et al. 2007) and reduce in size to approximately a third of their initial size [12], with most ending up as aerosol particles <20µm diameter (Tang et al. 2021a; Wei & Li 2015). Particles of this size are so light that they can be transported by room air currents, and so can remain airborne for many minutes (even hours), depending on their size. Once airborne they can travel considerable distances (i.e., many meters) (Nissen et al. 2020), with the heavier aerosol particles slowly settling out of the air.

The only exceptions to this are respiratory droplets >100µm that cannot fully evaporate to become aerosol particles (Tang et al. 2021a; Xie et al. 2007). These rapidly fall to the floor with an arcing motion (see Figure 1), usually landing about 1 to 1.5m away from the mouth. In Figure 3, which shows a sneeze, these can be clearly observed separating from the turbulent aerosol cloud and heading towards the floor. Although droplets of this size cannot travel far, they can contaminate surfaces and objects (fomites) close to the infectious person, as well as impacting on the eyes (Grajewski et al. 2021), or mucous membranes of the nose and mouth (PIP-Team 2011b; Weber & Stilianakis 2008), which contain ACE2 receptors (Grajewski et al. 2021). In clinical settings, infectious droplets potentially can pose a significant risk to healthcare workers (HCWs) nursing and treating Covid-19 patients.

58. While respiratory aerosol particles can float in air and remain suspended for considerable periods of time, the extent to which this occurs is governed by the size of the particle and the speed (velocity) of the air. Particles <10µm diameter can easily be transported many meters by the air currents that are normally found in rooms. However, particles much larger than this (e.g., 20 to 30µm) can be transported if the air currents are strong enough, as frequently occurs in the warm air convection currents (thermal plumes) that rise above the heads of people and heating elements (e.g., radiators) indoors (see paragraphs 86 to 88 for details).

59. Aerosol particles tend to travel wherever the air currents take them. However, if the air becomes still and stagnant (say, due to poor ventilation), then the particles will tend to slowly settle out due to gravity. The rate of this settling process depends on the size of the aerosol particles and the air conditions in the room space, with slower air currents being less able to keep the particles airborne. In completely still air with no air currents, it can be calculated using Stokes' Law (see Table 1) that a 10µm particle will take about 8 minutes to fall 2 metres, whereas a 5µm particle will take approximately 32 minutes to fall the same distance. From this it can be seen that smaller respiratory aerosols can remain airborne for considerable periods of time.

Table 1: Time taken (and velocity) for respiratory particles of various sizes to fall 2m in still air. Times have been computed using Stokes' Law.

	1µm	2µm	3µm	4µm	5µm	10µm	20µm	30µm
Terminal velocity (mm/s)	0.04	0.16	0.36	0.64	0.99	3.98	15.91	35.79
Time (minutes)	717.0	193.2	88.2	50.3	32.4	8.2	2.1	0.9

60. In addition to slowly settling out of the air due to gravity, respiratory aerosol particles are also attracted to surfaces that have a static electric charged, such as plastic aprons, plastic curtains and monitor screens (Shepherd et al. 2010)* – all of which are found in hospitals. Aerosol particles can also be removed through room ventilation, which is the process whereby clean outside air is introduced into a room space to flush out any virus and other pollutants. While this does not completely remove all infectious aerosols from the room air, it does dilute and reduce the concentration of aerosols in the air to safer levels. This means that the eventual fate of most exhaled virus particles is not to be inhaled, but rather, to be removed by a combination of these environmental mechanisms. Biological decay may also over time, affecting the ability of the virus to cause infection (Van Doremalen et al. 2020b). However, in the context of the aerosol transmission of SARS-CoV-2, the implications of this are not fully understood. Notwithstanding

this, it is important to note that despite the high attrition rate due to environmental factors, SARS-CoV-2 is so infectious that only relatively small numbers of viruses are required to infect susceptible individuals (Alsved et al. 2023b; Sinclair et al. 2024)*.

61. One of the main drivers of air circulation within room spaces are thermal plumes, the buoyant columns of warm air that rise vertically above warm/hot objects such as humans and radiators (heat emitters), etc. (Beggs et al. 2024; Bhagat et al. 2020)*. These promote air circulation within room spaces, with the result that complex convection currents are formed which direct the transport of aerosols. This can lead to the formation of regions of high and low aerosol concentration within the same room space simultaneously. Consequently, some people in a room may be at more risk than others, simply because they are located in a region where the respiratory aerosol concentration is higher, and therefore, they are potentially exposed to more virus.

62. All human beings are surrounded by a personal thermal plume, comprising of upward flowing convective air currents (see Figure 6), which can exhibit air velocities greater than 10cm per second (Craven & Settles 2006) and so are capable of transporting upwards respiratory aerosol particles up to about 30μm in diameter. While outdoors, these thermal plumes simply cause respiratory aerosols to be dispersed upwards away from susceptible individuals, indoors, aerosol particles that become entrained into a thermal plume are trapped by the room ceiling (see Figures 7 and 8). This means that when they reach the top of the room, the aerosols tend to fan out along the underside of the ceiling before descending back towards the floor, passing through the breathing zone where they can be inhaled (Beggs et al. 2024)*, as illustrated in Figure 8. The interaction between thermal plumes and ceilings is unique to the internal environment and is one of the main drivers of air circulation within room spaces (Bhagat et al. 2020).

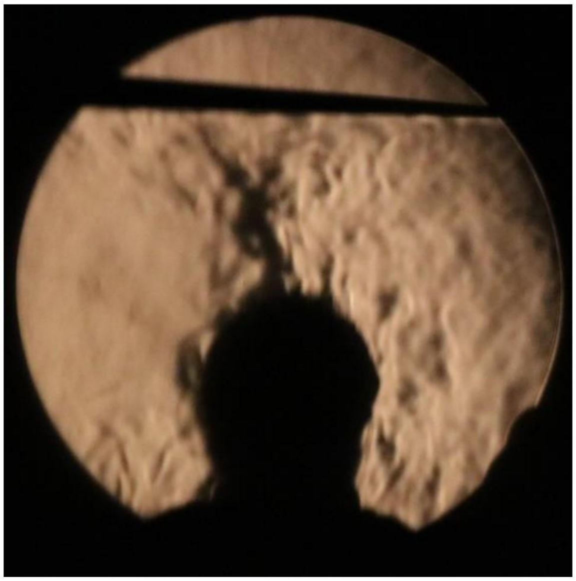


Figure 7. Schlieren photograph showing a thermal plume being trapped by a ceiling. (*Courtesy of Dr Fariborz Motallebi and Dr Eldad Avital of Queen Mary University of London*). (Beggs et al. 2024)*

63. The illustration in Figure 8 was produced using computational fluid dynamics (CFD) and shows the distribution of 5μm respiratory particles exhaled by an infected person (on the right) at several points in time following 5 seconds of speech in a poorly ventilated room (Beggs et al. 2024)*. The

susceptible person on the left is standing 2m away from the infected person on the right. From this it can be seen that, although initially projected forwards from the mouth, the exhaled aerosol particles quickly rise due to the action of the thermal plume (also shown) and the buoyancy of the warm breath, as seen at t = 15 seconds (top left). However, at the ceiling, the upwards trajectory of the particles is halted at t = 25 seconds (top right), resulting in the formation of a buoyant aerosol bolus containing a high concentration of particles. This proceeds to travel horizontally along the underside of the ceiling at t = 40 seconds (bottom left) and is deformed due to the action of the thermal plume of the person on the left and the settling out of particles due to gravity. This flow pattern is further amplified at t = 55 seconds (bottom right), demonstrating the strong combined effect of the ceiling and thermal plumes, resulting in the person on the left being exposed to a significant concentration of infectious aerosol particles after just 40 seconds, despite being 2m away from the speaker.

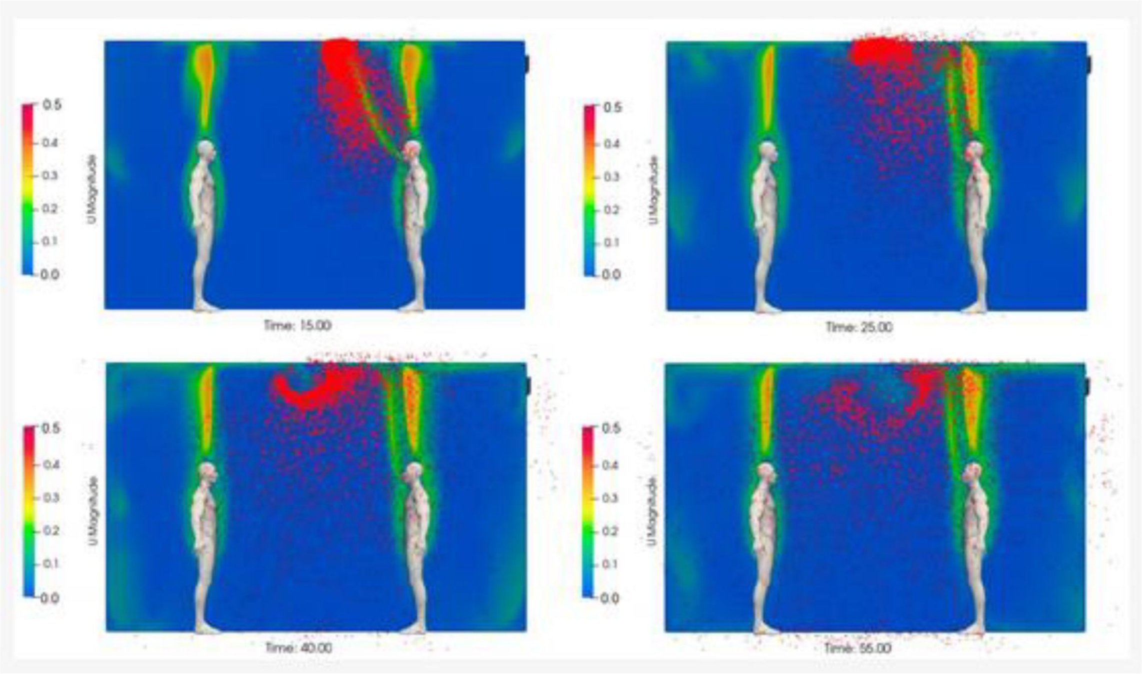


Figure 8. CFD results that illustrate the impact of thermal plumes on the distribution of 5 µm aerosol particles after a 5 s speech event between two standing people meeting in a small room with minimal ventilation. The velocity magnitude contours denoted by colours are plotted for the room's mid-cross section plane in metres per second, the time is in seconds, and the particles have been enlarged for clarity. The two people stand at 2 metres apart in a room of (4.2, 3.1, 2.7) m. (Beggs et al. 2024)*

Inhalation

Key findings:

- When aerosols are inhaled, the different sized particles land in different places within the respiratory system.
- The smallest particles, which are more likely to contain virus, tend to travel deep into the lungs, while the larger aerosol particles land in the mouth and throat.
- The amount of virus inhaled depends on the concentration of virus in the room air and the length of time spent in the room space.
- The longer someone spends in a room with an infectious person, the more virus particles they are likely to inhale.

64. Although in theory, particles of any size up to about 100μm diameter can be inhaled, in practice, about 90% of viral transmission at the nasopharynx (the anatomical region at the top of the throat joining with the nasal cavity) is thought to be due to particles in the size range 2.5 to 19μm (Basu 2021), with a median diameter of about 10μm (Hanes et al. 2004; Sosnowski 2021). This means as a rough 'rule of thumb', aerosol transmission of the SARS-CoV-2 virus is primarily associated with the inhalation of infectious particles <20μm diameter, although larger sized aerosol particles may be inhaled when individuals are directly exposed to coughs and sneezes (Bourouiba 2020).

65. Historically, there has been considerable ambiguity regarding the eventual fate of particles in this size range once they are inhaled. Generally, the term '**droplet nuclei**' has been reserved for the smallest aerosol particles which are able to travel deep into the lungs. However, some define 'droplet nuclei' as being <5μm diameter (i.e., the value usually stated in the medical literature), while others use <10μm as the cut-off threshold. The truth is that there is no firm cut off size. There is actually a continuum, with the larger aerosol particles generally impacting on the upper airways of the nasopharynx, and smaller particles able to travel deeper into the lower respiratory tract and lungs (Fennelly 2020; Hanes et al. 2004; Sosnowski 2021). While most particles in the size range 5 to 10μm will impact (land) in the upper airways, some will travel down into the lungs. However, in the size range <5μm, many more will be able to reach the lungs, although many will still impact in the upper airways.

66. Aerosol particles tend to be light and slow moving, and as such are easily inhaled. By contrast, droplets larger than 100μm diameter cannot be inhaled because they are relatively heavy and behave like a thrown object (Wang et al. 2021a). This means that they travel relatively fast and fall to the ground quickly, making them difficult to inhale. However, if a susceptible person is close to an infectious person then there is the potential for droplets transmission via the eyes (Grajewski et al. 2021), or mucous membranes of the nose and mouth (PIP-Team 2011b; Weber & Stilianakis 2008) to occur, although the extent to which this happens is not known.

67. Because exhaled respiratory aerosol particles are suspended in air, the quantity that will be inhaled by others is directly proportional to: (i) the concentration of particles in the air; and (ii) the volume of air that is inhaled. Therefore, if an infectious person with Covid-19 is present in a room space, the more room air that is inhaled by susceptible individuals, the greater the chance of someone becoming infected. In turn, the amount of air that is inhaled depends on the breathing rate (typically 6 to 9 litres per minute for healthy adults at rest), and the length of time spent in the room space. So, if a susceptible individual spends two hours in the same room space as an infectious person, then they are going to be at much greater risk of acquiring an infection

compared with someone who is only exposed for five minutes, all else being equal. Furthermore, when performing exercise or other activities the breathing rate can greatly increase, putting individuals at increased risk. For example, a typical adult engaged in moderate-intensity walking will have a pulmonary ventilation rate (i.e., the inhaled volume flow rate) in the region 20 to 40 litres per minute.

68. Covid-19 infection is initiated when spike proteins on the SARS-CoV-2 virus bind to ACE2 receptors in the cells lining the nose, mouth, nasopharynx and lungs. Similarly, influenza binds sialic acid receptors in the upper respiratory tract and lungs. So, in theory respiratory infections can be initiated by viruses binding to the appropriate receptors at any location within the respiratory tract. However, there is some evidence that the viral dose needed to cause an infection may be less if is delivered directly to the lungs in an aerosol. In a 1966 study, Alford et al. (Alford et al. 1966) found that illness could be induced in human subjects with a substantially lower dose when the influenza virus was administered in small aerosol particles rather than by nasal drops. However, such experiments are no longer conducted because of safety concerns, with nasal inoculations the norm in present-day studies. Therefore, it is difficult to draw firm conclusions on this subject. Notwithstanding this, it has been observed that natural influenza infections tend to produce more severe symptoms compared with those induced in the laboratory using nasal inoculation (Little et al. 1979), reinforcing the suspicion that aerosol transport might be a feature of influenza transmission.

Risk of inhaling an infectious dose

Key findings:

- The risk of contracting an infection is related to the concentration of virus particles in the air and the length of time spent in the room space.
- The longer someone spends in a room breathing contaminated air, the more likely it is that they will become infected.
- Even with relatively low concentrations of virus in the air, if someone spends long enough in a room space, then they may be at risk of becoming infected.
- However, if the viral load in the air is high, then only a short exposure time may be required in order for someone to become infected.

69. With airborne viral infections, the risk of acquiring an infection is directly proportional to the number of virus particles that are inhaled. So, the greater the number of SARS-CoV-2 virus particles inhaled, the higher the chance of one of them coming into contact with an ACE2 receptor and initiating an infection (Beggs et al. 2024)*. While many thousands (even millions) of virus particles per hour may be shed by infectious individuals (Ma et al. 2021), because they are so small (see paragraph 29) it means that thousands of viruses are able to fit in a single aerosol particle. Consequently, the likelihood is that the virus will be unevenly distributed, with some respiratory particles containing virus, and others not. This means that many of the respiratory particles inhaled will not contain virus. However, while we do not know which aerosol particles contain virus, it is nonetheless true that the greater the number of respiratory particles inhaled, the higher the likelihood that some will contain virus. Therefore, the risk of acquiring a Covid-19 infection by the airborne route is directly proportional to the number of respiratory aerosol particles inhaled.

70. From this we can see that chance contributes greatly to whether or not an individual exposed to an infectious aerosol will contract an infection. For a SARS-CoV-2 infection to occur the following events must happen: (i) the inhaled respiratory aerosol must contain the virus; (ii) the aerosol particles that come into contact with the ACE2 receptors must contain viruses; (iii) the virus particles in the aerosol must be fit enough to bind to the ACE2 receptors and enter the host's cell; and (iv) once inside the cell, the virus must overcome the host's immune defences and be able to replicate. If the process fails at any of these stages, infection cannot occur. Consequently, because many virus particles will either miss the target ACE2 receptors, fail to bind because they are damaged, or be overcome by the host's immune system, it means that generally a large number of virus particles need to be inhaled (i.e., the expected infectious dose) in order for a few to establish an infection (Prentiss et al. 2022).

71. Genetic 'bottleneck' studies have shown that most SARS-CoV-2 (Lythgoe et al. 2021; Sinclair et al. 2024)* and influenza (McCrone et al. 2018) infections are initiated by just a few virus particles (i.e., in the region 1 to 8 viruses); something that is consistent with these infections being transmitted in aerosols. Indeed, Sinclair et al. (Sinclair et al. 2024)* estimated that between 33% and 75% of Covid-19 cases are initiated by a single viral particle. However, in order for these few viruses to hit the target and establish an infection, many more need to be inhaled (Beggs et al. 2024; Prentiss et al. 2022)*. With some viral diseases, this ratio can be several thousands to one, while with other more contagious infections, the ratio might be a few hundred to one (Zwart et al. 2009). In other words, when an infection is highly contagious, the expected infectious dose will be low, with only relatively few virus particles needing to be inhaled (i.e., several hundred) in order to initiate an infection. With Covid-19, it has been estimated that the expected infectious dose for SARS-CoV-2 in humans is thought to be approximately in the range 300 to 2000 virus particles, with an average (median value) being about 600 virus particles (Prentiss et al. 2022).

72. To put this in to perspective, assuming that it takes on average 600 virus particles to initiate a COVID-19 infection, if an adult sits at rest in a room for two hours and inhales air with a relatively low viral concentration of 10 viruses per m^3, then according to Beggs et al. (Beggs et al. 2024)* the expected chance of acquiring a SARS-CoV-2 infection would be 1.6% (i.e., probability = 0.016) (see Appendix 1 for details of calculation). What this means in practice is that for every 100 people exposed to this dose, between one and two people will become infected, which is a relatively high number. However, because this is theoretical calculation, it should be treated as being indicative only. Nonetheless, it illustrates the point that relatively low concentrations of viable virus in the air have the potential to cause infection.

73. Importantly, both exposure time and the concentration of virus in the air are critical. In theory, someone can receive the same infectious dose if they inhale air with a high viral load for a short time, or alternatively, if they inhale air with a low concentration for a much longer period of time. So, if a susceptible person spends a long time in the same space as an infectious individual, even though they may be seated some distance away (i.e., much further than 2 m), they can still inhale enough virus to initiate an infection. Indeed, the longer they stay in the same space as the infector, the greater the risk of infection.

74. In situations where the viral load is allowed to accumulate in air, say in a poorly ventilated room (see paragraph 86 for details), even relatively short exposure times can result in significant risk. This is especially the case in situations where individuals may be shouting, singing, or just talking loudly. Indeed, Alsved et al. (Alsved et al. 2023b) calculated that in the context of singing, a susceptible person could inhale an infectious dose of SARS-CoV-2 in just 6 to 37 minutes, depending on the room ventilation rate.

Near-field and far-field transmission

Key findings:

- Small respiratory aerosols remain airborne for long periods, and in enclosed spaces their concentration in the air will build up over time.
- When considering infection risk the terms near-field and far-field (i.e., less than and greater than 2 metres away from an infectious person) are helpful when describing different types of exposure.
- If an infectious person with Covid-19 is in a room, then the viral load will quickly build-up in the room air, with the result that everyone in the room space is potentially at risk of acquiring an infection due to far-field exposure.
- However, individuals within 2 meters in front of the infectious person are more likely to be exposed to higher virus concentrations in the near-field.
- The far-field risk of infections is proportional to the length of time someone spends in the same room space as an infectious person.

75. When assessing infection risk, it is often helpful to distinguish between the near and far-fields. In rooms and other enclosed spaces, infectious aerosols pose both a '**near-field**' and a '**far-field**' threat, with the near-field being close proximity to the infected person (i.e., 1 – 2m) and the far-field generally considered >2m away. The near-field transmission risk occurs due to the cone-shaped plume (cloud) of aerosol particles that is exhaled when speaking, singing, shouting, or breathing (see Figure 9 which shows a Schlieren photograph of a person talking (Beggs et al. 2024)*) (Wei & Li 2015), and which has the potential to infect susceptible individuals in close proximity (Tang et al. 2021a; Tang et al. 2021b). This aerosol plume is turbulent and expands in volume as it sucks in (entrains) air from the surrounding room space (Bourouiba 2020; Li et al. 2022). This means that the concentration of virus in this plume will depend not only on what is exhaled by the infector, but also on the concentration of virus in the wider room (Li et al. 2022). Importantly, if the room is poorly ventilated, then the exhalation plume will tend to contain a higher viral load (Li et al. 2022).

Figure 9. Schlieren photograph of a person talking. Notice: (i) the cone-shaped turbulent exhalation jet emanating from the mouth; and (ii) the vertical thermal plume passing over the

face and head. (Courtesy of Dr Fariborz Motallebi and Dr Eldad Avital of Queen Mary University of London). (Beggs et al. 2024)*

76. Importantly, near-field transmission has a directional component with face-to-face interactions posing a greater risk compared with side-by-side or back-to-back arrangements. By comparison, the far-field transmission risk is non-directional and arises when the aerosol particles have been dispersed by air currents into the wider room space. It is termed 'far-field' because the dispersed aerosols pose a threat to all those who are in the same space, and not just those in close vicinity to an infector (SAGE-EMG 2020c). Having said this, aerosol particles are so light that they can rapidly migrate between rooms due to the air currents generated by people moving, thermal plumes, and wind pressure, etc. (Burridge et al. 2021)*, as Butler et al. demonstrated on a medicine for the elderly hospital ward (Butler et al. 2023a; Butler et al. 2023b)*. Therefore, far-field exposure also includes transmission between spaces involving aerosols suspended in air. Rarely, far-field exposure has also been reported due to air flow between different rooms. In an outbreak in a managed isolation and quarantine facility in New Zealand, where pathogen genomics was used to demonstrate that aerosol transmission between two individuals in different rooms with a shared corridor had likely taken place (Eichler et al. 2021).

77. In addition to the inhalation of infectious aerosols, larger virus-laden droplets are also a potential risk in the near-field (as explained in paragraph 31). When people are in close proximity to each other, these can easily traverse short distances and impact on the eyes (Grajewski et al. 2021), or mucous membranes of the nose and mouth (PIP-Team 2011b; Weber & Stilianakis 2008). In theory, this can lead to the transmission of respiratory viral infections. While this route is plausible, the epidemiological and modelling evidence supporting it is relatively weak and inconclusive (PIP-Team 2011b), with the opinion that droplets a play a major role based largely on the assumption that the vast majority (i.e., about 99% according to (PIP-Team 2011b)) of the viral material is contained in the larger droplets (Nicas et al. 2005; PIP-Team 2011b; Weber & Stilianakis 2008). However, recent scientific advances challenge this assumption, with many studies involving SARS-CoV-2 (Alsved et al. 2023a; Coleman et al. 2022; Jaumdally et al. 2024; Tan et al. 2023) and influenza (Bischoff et al. 2013; Coleman & Sigler 2020; Cowling et al. 2013; Kormuth et al. 2018; Lednicky & Loeb 2013; Lindsley et al. 2010b; Yan et al. 2018) patients showing that the smallest respiratory particles <5μm diameter are the ones most likely to contain virus. Consequently, this suggests that the viral load in larger droplets is probably not a high as originally assumed, and casts doubt on the importance of the so-called "droplet route" in the transmission of SARS-CoV-2 and influenza, as some animal (Andrewes & Glover 1941; Kutter et al. 2021) and modelling (Atkinson & Wein 2008) studies have suggested. So, in summary, while large droplet transmission is plausible, there is growing evidence that this route may be less important than previously thought.

78. Irrespective of whether transmission is near or far-field, the infection risk associated with inhalation ultimately depends on the number of viral particles that are inhaled by susceptible individuals. As such, contracting a Covid-19 infection appears to be dose related and is affected by: (i) the concentration of SARS-CoV-2 virus in the air that is inhaled; (ii) the duration of exposure; and (iii) the quantify of air is inhaled per minute. This latter point is often overlooked, but essentially it means that if someone is doing physical exertion (e.g., bed making, floor cleaning, lifting patients, etc.), then they are likely to be inhaling more air than when seated at rest, and therefore potentially at greater risk.

79. Historically, the term 'long-range' has often been used instead of 'far-field' (PIP-Team 2011b). However, the term 'long-range' is ambiguous and makes no distinction between, say, 3m and

20m away. Consequently, 'long-range' can mean different things to different people, and is therefore difficult to interpret. By comparison, 'far-field' refers to everywhere in a room space (or adjacent space) that is not directly in the infectious person's exhalation plume (or thermal plume), which is generally taken to extend about 2m from the mouth and nose. So, in summary, a near-field threat is experienced only by those who are positioned <2 m in front (or above) on an infectious person, while everyone else in the same space is considered to experience a far-field threat. In the clinical context, this means that when nursing or treating patients, HCW's are generally exposed to a near-field risk, because they are positioned directly in front or above patients, and therefore may be exposed to infectious aerosols either from the patient's exhalation plume or entrained into their thermal plume. By comparison, non-clinical staff such as cleaners can still be at risk from far-field transmission.

80. The near-field transmission risk occurs due to the cone-shaped exhalation which expands in volume as it entrains (sucks in) air from the surrounding room space (Beggs et al. 2024; Bourouiba 2020; Li et al. 2022)*. Outdoors, this exhaled aerosol plume rapidly becomes diluted and dissipates the further away one travels from the infectious person, with the result that the far-field risk of acquiring an infection becomes very low (i.e., approaching zero) (Beggs et al. 2024)*. However indoors, because the space is confined, the exhaled aerosols will tend to become trapped in the room (especially by the ceiling), with the concentration building-up over time (Beggs et al. 2024)*. The extent to which this build-up occurs, depends on two factors: (i) the rate at which respiratory aerosols are produced, with singing and shouting, producing many more particles than talking and breathing (Alsved et al. 2020); and (ii) the rate at which aerosol particles are removed from the space by ventilation or air cleaning. Therefore, spaces that are better ventilated tend to reduce the far-field infection risk, because the ventilation air dilutes the concentration of aerosol particles that are inhaled.

81. The build-up and decay of infectious aerosol particles in room spaces is illustrated in Figure 10, which is reproduced from the CDC website (CDC 2023b). This contrasts aerosol build-up and decay in a poorly ventilated room with that in a well-ventilated space. The images on the left illustrate the situation when an infectious person has just exited a room (at 2:30 pm) which they had previously occupied, say, for several hours. If the room is poorly ventilated (top left), then the concentration of infectious aerosol particles in the air can build-up to a high level, whereas in the space with good ventilation (bottom left), while aerosol build-up still occurs, the concentrations reached are much lower, with the result that space is safer of susceptible individuals. Over time, the aerosol concentration levels in the empty room will reduce as the particles gradually settle out of the air or are flushed away by the ventilation air. So that by 3:30 pm, the concentrations in the air will be much less. However, in the room with good ventilation (bottom right), the extent to which this will happen is much greater than in the poorly ventilated space (top right).

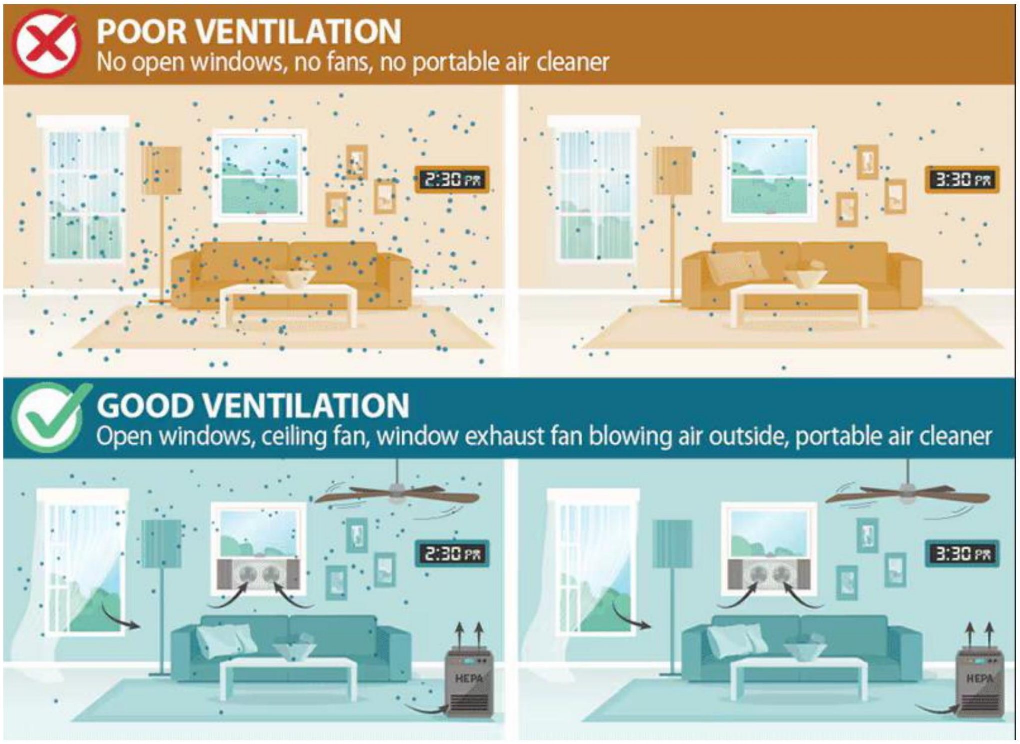


Figure 10. Illustration of the effects of poor and good ventilation on a room containing infectious respiratory aerosols, immediately after the infectious person has exited the space at 2:30 pm. The top panel shows the aerosol concentrations in the air at 2:30 pm and 3:30 pm, whereas the bottom panel shows the same scenario for a well ventilated room. (Illustration from CDC website (CDC 2023b))

82. As explained above, the risk of acquiring an infection in the far-field depends on the concentration of infectious aerosols in the room air, and the time spent by individuals in the space, and the breathing rate; the longer the exposure time, the greater the risk. This principle forms the basis of the well-known Wells-Riley epidemiological model that has been used for over 50 years to assess the risk of acquiring airborne infections such as TB and measles (Beggs et al. 2003; Nardell et al. 1991; Noakes et al. 2006a; Riley et al. 1978; Riley 2001).

83. Importantly, duration of exposure is a key factor in understanding the far-field transmission of disease mediated by aerosols. Yet, there has been a tendency amongst some commentators (PIP-Team 2011b; Weber & Stilianakis 2008) to ignore exposure time, and instead, focus purely on the viral load in respiratory aerosols (PIP-Team 2011b). However, this can potentially result in an underestimation of the far-field risk posed by infectious aerosols indoors. Although the viral load contained in individual aerosol particles might be relatively small (PIP-Team 2011b), over time, in an enclosed space, susceptible individuals can inhale many thousands of aerosols, which cumulatively may amount to inhalation of a substantial viral dose (Beggs et al. 2024; Nardell et al. 1991; Noakes et al. 2006a)*. So, individuals who spend several hours in the same space as an infectious person may become infected even though they are not in close proximity to the infector, as happened with tragic consequences in the Covid-19 outbreak inflicted on the Skagit County choir (Hamner et al. 2020; Miller et al. 2021).

84. In a clinical context, exposure time is an important issue that is often overlooked, and which affects some groups more than others. This is because the risk of onward transmission is directly proportional to the length of time that a susceptible person spends near or in contact with an

infectious person. So, in this respect, patients are particularly vulnerable, because they can spend up to 24 hours a day in the same location on a hospital ward. This means that if one patient in a six-bed bay becomes infected with SARS-CoV-2 (assuming that they are not removed and isolated in a separate room), then the five other patients in that bay will be continually exposed to an elevated concentration of infectious aerosols in the air, putting them all at risk. Likewise, HCWs who spend more time with infected patients, such as nurses and healthcare assistants, will be at greater risk, compared to staff such as medical consultants who might only make a passing visit to each bed or room. As such, exposure time is an important issue, which has far-reaching implications on the way in which patients, staff and wards should be managed, especially during epidemic (pandemic) conditions.

85. Much remains unknown about the relative contributions of near-field and far-field exposure to the transmission of SARS-CoV-2. While it is suspected that near-field respiratory aerosol transmission might be more dominant, observations from superspreading events suggest that far-field transmission might also be influential (Chen et al. 2021a; Miller et al. 2021). Therefore, there is need for more research to better understand the relative contribution of both to the burden of respiratory viral disease.

Indoors and outdoors

Key findings:

- The risk of becoming infected with Covid-19 is much greater indoors compared with outdoors.
- This is because the virus concentration in the room air builds up over time, whereas outdoors it is quickly dispersed by the breeze.
- Indoors, the ceiling traps any infectious respiratory aerosols that are transported upward by the thermal plumes that surround people, whereas outdoors there is no ceiling and so any infectious aerosols are quickly dispersed.

86. The risk of contracting a Covid-19 infection is much greater indoors than outdoors, with the odds of contracting a SARS-CoV-2 infection indoors estimated to be almost 19 times higher than that outdoors (Bulfone et al. 2020). While the reasons for this are not fully understood, in confined indoor spaces, when an infectious person is present, the concentration of viral particles in the air will tend to increase over time, particularly if the space is poorly ventilated, increasing the far-field risk of cross-infection occurring – something that cannot happen outdoors.

87. Another fundamental difference between internal and external environments is that indoor spaces have ceilings and outdoor spaces do not. This has a profound effect on aerosol transport in the two environments. All human beings, whether indoors or outdoors, are surrounded by a personal thermal plume, comprising of an upward flowing convective air current (see Figure 7). When outdoors, these thermal plumes simply cause respiratory aerosols to be dispersed upwards away from susceptible individuals. However, indoors, aerosol particles that become entrained into a thermal plume are trapped by the room ceiling (see Figures 7 and 8). This means that when they reach the top of the room, the aerosols tend to fan out along the underside of the ceiling before descending back towards the floor, passing through the breathing zone where they can be inhaled (Beggs et al. 2024)*.

88. The interaction between thermal plumes and ceilings is unique to the indoor environment and is one of the main drivers of air circulation within room spaces (Bhagat et al. 2020), especially when

poorly ventilated. As such, the air in room spaces can become unevenly mixed, with complex convection currents directing the transport of aerosols. This can cause regions of high and low virus concentration to co-exist within at the same time within room spaces, something that generally does not happen outdoors.

89. Air velocities are generally much higher outdoors compared with inside buildings, even when it is not windy. This means that when outside, exhalation plumes from infectious individuals tend to be interrupted by the increased air movement, and thus are more rapidly dispersed compared with indoors. Consequently, the near-field infection risk tends to be reduced outdoors.

Fomite and contact transmission of respiratory viruses

Key findings:

- Contact transmission involves physical touch, either from an infected person straight to an uninfected person, or via an inanimate object such as a door handle, known as a “fomite”.
- As with other routes, contact transmission requires a sufficiently large amount of live virus to be transferred.
- Several processes contribute to the degradation or reduction of live virus: more time spent outside the host, additional steps in the process of contact transfer, and the type of surface - with skin or porous inanimate surfaces being less conducive to virus survival than smooth surfaces like stainless steel.
- It was assumed at the onset of the Covid-19 pandemic that contact transmission was a major contributor to transmission, but there was little evidence of this from studies of other respiratory viruses.
- Evidence for the effectiveness of handwashing in Covid-19, influenza and other respiratory viruses is mixed, showing only modest benefits.
- Transmission through the air is likely more important than contact routes, though occasional contact transmission is also possible.
- Studies early in the Covid-19 pandemic detected viral genetic material on frequently touched surfaces, but could not determine the proportion of overall transmission that was due to contact as opposed to transmission through the air.
- Real-world epidemiological studies detecting infection outcomes, rather than just presence of the virus, often cannot discriminate between close-range transmission through the air and contact transmission.
- The assumption that contact routes are a major contributor to transmission was flawed, and led to many IPC policy-makers, practitioners and researchers requiring a higher standard of causal evidence to accept that airborne transmission was occurring than they required for contact transmission.

90. Historically, influenza and other respiratory viral infections, such as SARS-CoV-2, have been assumed to be primarily transmitted via the droplet route and by various contact routes (HPIH&SD_PIP 2009; WHO 2014; WHO 2020). In this section we examine the reasons for believing that the contact route plays a significant role in transmission, and the evidence supporting this assumption. In addition, we highlight the far-reaching ramifications that this assumption has had on IPC policy and practice.

91. When considering this subject, it is helpful to divide the potential transmission routes into two broad classes: (a) **direct routes**, which involve no intermediary steps; and (b) **indirect routes**, which involve one or more intermediary steps. Respiratory transmission can be considered a direct route, because the viruses contained in respiratory particles travel directly from the infectious host to the target receptors of susceptible individuals, without touching any intermediate surfaces. By contrast, indirect routes involve contamination of intermediary surfaces, be they hands or inanimate surfaces and objects (fomites). Rather confusingly, so called 'direct contact' routes, such as hand-to-hand or hand-to-face contact, are technically indirect routes because they involve the virus contaminating one or more hands *en route* (PIP-Team 2011b). For example, consider an infectious person who covers their mouth with their hand while coughing, and then shakes the hand of a susceptible person. In order for cross-infection to occur, virus particles must be physically transferred, in large enough numbers: (i) from the mouth of the infectious person to their hands; (ii) from the infectious host's hand to the susceptible person's hand; and (iii) from the susceptible person's hand to their nose, mouth or eyes. **Fomite transmission** is similar, but involves contamination of inanimate surfaces and objects (e.g., door handles, light switches, bedside cabinets, etc.), potentially introducing additional steps into the chain of infection. Importantly, with fomite transmission, surface/object contamination can occur either through contact with contaminated hands, or by infectious large droplets falling onto surfaces. In theory, surface contamination might also occur via the slow deposition of infectious aerosol particles settling out of the air, although the extent to which this happens is not known.

92. Importantly, at every stage along an indirect chain, viral material is either lost or degraded (damaged) (Pancic et al. 1980; Zhang & Li 2018). So often, not enough viable virus particles reach the target receptors of a susceptible person, with the result that no infection occurs. So, the more intermediary surfaces involved in the chain of infection, the greater the chance that the quantity of viral material transferred will be insufficient to cause an infection. Similarly, the longer the period of time viral material resides on a surface, the more it will degrade, and eventually a point will be reached when it is no longer viable (i.e. can no longer cause an infection) (Owen et al. 2021; Van Doremalen et al. 2020b; Xu et al. 2023). This distinction is important because many scientific studies use polymerase chain reaction (PCR) techniques to detect the presence of viral material on surfaces and in the air. However, while these techniques can detect the presence of genetic material from a virus, they cannot tell whether or not the virus is viable and able to cause infection. Indeed, it is likely that most viral material found in the environment using PCR is non-viable. In order, to determine whether or not virus samples are viable, is necessary to use culturing (growing) techniques, although these can be technically challenging, and are therefore undertaken less often.

93. By comparison, respiratory transmission, being a direct route, involves no intermediate steps where viable viral material can be lost, although viral material is still degraded over time. Also, compared with fomite transmission, direct routes are much quicker, with the process generally lasting seconds (larger droplets) or minutes (smaller aerosols), depending on the ventilation and air movement conditions. Consequently, less time will elapse in which the virus can degrade compared with other routes of transmission. Having said this, it is known that viruses in aerosols

can undergo degradation fairly rapidly (minutes to hours), depending on temperature and humidity (Beggs & Avital 2021; Oswin et al. 2022; Van Doremalen et al. 2020b)*, and so the amount of infectious viral material inhaled will depend on the age of the aerosol. With respect to this, there are wide discrepancies in the degradation rates observed for SARS-CoV-2 in aerosols by various researchers, with for example, van Doremalen et al. (Van Doremalen et al. 2020b) estimating the half-life (i.e., the time required for a 50% reduction) to be about 1.1 hours (similar to that found by other researchers (Dabisch et al. 2020; Schuit et al. 2020; Smither et al. 2020)), whereas Oswin et al. (Oswin et al. 2022) observed a 50% reduction in viability after just 5 seconds, and an 80% reduction after 10 minutes at normal room conditions. While the reasons for this large discrepancy is not known, it is noticeable that these researchers used completely different experimental methodologies, with the latter using a novel electromagnetic levitation methodology, and the other researchers all using a Goldberg drum. So, it is likely that the observed differences reflect the different methodologies used, making comparison between the two difficult. Consequently, there is still uncertainty about how long viable SARS-CoV-2 can persist in aerosols. Having said this, with near-field transmission the inhaled aerosols are likely to be only a few seconds or minutes old, and so there a not much time in which the viral material can degrade.

94. The stability of SARS-CoV-2 on environmental surfaces has been shown to vary greatly depending on the porosity, temperature and humidity (Chin et al. 2020; Liu et al. 2021; Owen et al. 2021; Van Doremalen et al. 2020b; Xu et al. 2023), with the virus generally decaying much faster on porous surfaces such as paper, cardboard and fabric, compared with smooth hard surfaces (e.g., steel, glass, etc.) (Fusco et al. 2023; Hosseini et al. 2022; Liu et al. 2021; Owen et al. 2021; Xu et al. 2023). For example, in a systematic review conducted in 2023, Xu et al. (Xu et al. 2023) found that the half-life of SARS-CoV-2 was generally 5 – 9 hours on non-porous surfaces and 1 – 5 hours on porous surfaces. However, there was huge variation between studies, with half-life times ranging from a few minutes to several days for both porous and non-porous surfaces. Although much uncertainty still remains, from this it appears clear that large amounts of SARS-CoV-2 can persist on inanimate surfaces for several hours, with the decay generally being faster on porous surfaces compared with those that are non-porous. Similar findings have been observed for influenza, with a 99% reduction in viable influenza occurring after: 174.9 hours on stainless steel; 34.5 hours on microfibre; and 17.7 hours on cotton (Thompson & Bennett 2017).

95. Similar experiments involving SARS-CoV-2 and influenza on the hands of subjects have shown that survival time is significantly shorter on human skin compared with stainless steel, glass and polystyrene, with the half-life times for SARS-CoV-2 and influenza being 3.5 and 0.8 hours, respectively (Hirose et al. 2021). Others have observed similar results for influenza, with infectious virus detectable on only a small minority of subject's fingers 30 minutes after inoculation (Thomas et al. 2014), and a >99% reduction in viable viral load occurring on the fingers of most subjects within 2 minutes (Grayson et al. 2009). As such, this suggests that for both viruses (and influenza, in particular), human hands are much less conducive to survival than many inanimate surfaces (Geng & Wang 2023).

96. With all the indirect routes, including fomite transmission, the final step in the process is contaminated hands touching the nose, mouth or eyes of susceptible people (HPIH&SD_PIP 2009; WHO 2014). This assumption is foundational to the belief that fomite transmission and hand contact are involved in the spread of influenza and Covid-19. However, despite this assumption being at the heart of global IPC policy, the scientific evidence supporting it is weak. The problem is that there is no satisfactory physical mechanism exists to explain how the virus particles transfer from the hands to the ACE2 and sialic acid receptors in the nasal cavity and respiratory tract. Indeed, the 2011 Pandemic Influenza Preparedness (PIP) Team report, *Respiratory and Hand*

Hygiene in an Influenza Pandemic (PIP-Team 2011a), went as far as to state: ***"… the transfer of viable influenza virus from hands/fingers to the respiratory tract is controversial, because no experimental or epidemiological field studies have addressed this question."***. However, studies involving fingers inoculated (or contaminated) with RSV and rhinovirus (two of the viruses responsible for common cold symptoms) have been able to show that infections can be produced in volunteers who rub their fingers in their eyes (Goldmann 2000; Reed 1975). So, a biologically plausible mechanism exists that may describe infection via an ocular route, although this still does not explain how the virus might reach the receptors deep in the nasal cavity or respiratory tract. Nevertheless, the respiratory hygiene PIP report concludes: ***"In the absence of studies on influenza, and in the absence of studies that have shown that transmission does <u>not</u> occur from hands to nose and eye for other respiratory viruses, this transmission pathway could apply to many respiratory viruses"*** (PIP-Team 2011a). Similarly, the authors of the 2011 PIP Team report, *Routes of Transmission of the Influenza Virus*, state: ***"The contact route of transmission cannot be excluded; virus survival data shows that it is plausible"*** (PIP-Team 2011b). So importantly, what the authors of these two PIP reports are saying, is that although the evidence supporting the transmission of influenza via hands and fingers is weak, they cannot rule out the possibility that transmission of influenza by this route might still be occurring.

97. Prior to the Covid-19 pandemic, the epidemiological evidence for handwashing preventing the transmission of influenza and other respiratory viruses was mixed, although relatively modest benefits of increased hand hygiene were reported (PIP-Team 2011a; Warren-Gash et al. 2013). This led the PIP Team to conclude: ***"It was found that hand and respiratory hygiene interventions are biologically plausible interventions for influenza control, but that the expected effect size is likely to be small to moderate only"*** (PIP-Team 2011a). Furthermore, some studies found no beneficial effect (Simmerman et al. 2011), with others finding that hand hygiene was only beneficial against influenza when combined with the wearing of facemasks (Wong et al. 2014). Indeed, a 2014 meta-analysis study (Wong et al. 2014) of ten randomised controlled trials concluded: ***"Our findings highlight the potential importance of interventions that protect against multiple modes of influenza transmission, and the modest efficacy of hand hygiene suggests that additional measures besides hand hygiene may also be important to control influenza."***

98. With specific regard to Covid-19, the benefits of handwashing appear mixed. A 2022 rapid review (Khatib et al. 2022) of three studies on Covid-19 and ten on SARS, found that handwashing, sterilization of hands, gargling, or showing after attending Covid-19 or SARS patients was protective. Evidence also found that frequent washing of hands could prevent SARS transmission among healthcare workers. However, the certainty of the evidence supporting the benefits of improved hand hygiene according to the GRADE system were deemed very low. Similarly, the 2023 Cochrane review of the impact of handwashing on the spread of respiratory viruses (Jefferson et al. 2023) found evidence in favour of hand hygiene, although this was relatively weak. The reviewer's reported that a 14% relative reduction in acute respiratory infections was associated with improved hand hygiene, although no similar (statistically significant) improvement was observed for influenza. This led the Cochrane team to conclude: ***"Hand hygiene is likely to modestly reduce the burden of respiratory illness, and although this effect was also present when influenza like illnesses and laboratory-confirmed influenza were analysed separately, it was not found to be a significant difference for the latter two outcomes"*** (Jefferson et al. 2023).

99. Collectively, the evidence presented above indicates that the contact and fomite routes are likely to be less important in the transmission of Covid-19 and influenza than previously assumed, suggesting instead, that the 'through the air routes' are more dominant. However, this does not preclude the possibility that the contact/fomite routes make a minor, but significant, contribution

to the transmission of both diseases. During the Covid-19 pandemic, viral RNA was frequently recovered from commonly touched surfaces in hospitals such as door handles (Elbadawy et al. 2021; Moore et al. 2021; Zhou et al. 2023a; Zhou et al. 2023b), bed controllers (Moore et al. 2021), nurse call buttons (Moore et al. 2021) and computer keyboards (Moore et al. 2021; Zhou et al. 2023b), suggesting that the carriage (transfer) of virus particles on (and from) hands is a widespread phenomenon, despite the hand hygiene and surface cleaning/disinfection measures that regularly occur in hospitals. However, it is not known how much this contributes to the spread of either Covid-19 or influenza in hospitals. This is because both the quantity and quality (i.e., viability) of viral material is reduced every time the virus is transferred to and from a surface (Zhang & Li 2018). For example, in an experiment undertaken in 1980, Pancic et al. (Pancic et al. 1980) were able show that if donors, whose fingers were inoculated with rhinovirus, touched a brass door knob, only 12.5% of the viral load was subsequently transferred to recipients who handled the door knob 10 minutes later. Similarly, when the donor's and recipient's fingers made direct contact, only 5.9% of the virus was transferred. This suggests the amount of viable viral material transferred via hands, either directly or indirectly, is relatively small. For influenza, Tellier (Tellier 2009) came to a similar conclusion, calculating that the transmission risk was just 1% for hand-to-face contact.

100. In addition, viability being lost during the transfer process, enveloped viruses like influenza and SARS-CoV-2 decay over time (generally over several hours depending on the type of surface). This means that when fomite transmission occurs, it is most likely to happen shortly after the surface has become contaminated, which is likely to be a reasonably infrequent occurrence. For this reason, the PROTECT COVID-19 National Core Study currently (May 2024) states on its website that although transmission of respiratory viral infections is possible through touching contaminated surfaces and then touching the face, this is only likely to occur occasionally when the inoculation dose is large enough to cause transmission (PROTECT 2022).

101. Despite the fact that early in 2020 it was shown that SARS-CoV-2 could survive on surfaces for several hours (5-6 hour half-life) (van Doremalen et al. 2020a), there is relatively little epidemiological evidence to support the opinion that the fomite route makes a significant contribution to transmission of Covid-19. In fact, the first epidemiological evidence implicating contaminated surfaces in the transmission of Covid-19 was only published in April 2023 (Derqui et al. 2023). This study by Derqui et al., which involved the surveillance of 279 households from August 2020 until March 2021, found that the presence of SARS-CoV-2 RNA on frequently touched surfaces was significantly associated with a higher risk of susceptible contacts (i.e., people sharing a house with an infected person) becoming infected. As such, this was the first epidemiological study to confirm an association between surface contamination and the transmission of SARS-CoV-2.

102. However, it is important to note that although Derqui et al's study (Derqui et al. 2023) showed an association between environmental contamination and the risk of SARS-CoV-2 infection, it did not demonstrate a causal link. This is because an infectious person shedding enough virus to contaminate the surrounding environment, is also likely to be exhaling many thousands of infectious aerosol particles per hour, and these may have increased the risk of infection, rather than the contaminated surfaces. It could also be that the contacts in the study acquired an infection from outside the household. So, while the study provides evidence suggesting an association between environmental contamination and the transmission of SARS-CoV-2, it does not demonstrate causality, or quantify how much transmission is due to contaminated surfaces and objects.

103. In addition to hand contact, inanimate surfaces and objects can become contaminated when exhaled infectious droplets land on them. Fomite contamination by this route generally occurs close to an infectious individual because large droplets >100μm diameter quickly fall to the floor within about 1.5 m of their source. Historically, this has been considered one of the key routes by which respiratory viruses can be transmitted. However, the realisation that with influenza and

SARS-CoV-2, most of the exhaled viral load is found in small aerosol particles <5µm that can float in the air (Alsved et al. 2023a; Coleman & Sigler 2020; Coleman et al. 2022; Jaumdally et al. 2024; Lindsley et al. 2010b; Yan et al. 2018), challenges this assumption. This is because it implies that the viral load in larger droplets is likely to be less than previous thought. As such, this undermines the assumption that fomites contaminated by respiratory droplets will acquire enough virus in order to be able to transmit infection.

104. Many animal studies have shown that influenza is transmitted in particles that pass through the air, be they droplets or aerosols (Andrewes & Glover 1941; Kutter et al. 2021; Mubareka et al. 2009; Richard et al. 2020; Sutton et al. 2014). However, it is difficult with animals to quantify the importance of this route of transmission relative to the contact route. Notwithstanding this, in a study involving guinea pigs it was demonstrated that aerosols and droplets are a much more efficient route of transmission for influenza than contaminated fomites (Mubareka et al. 2009). As such, this is further evidence supporting the conclusion that the contaminated fomites might play a lesser role in the transmission of respiratory infections than previously thought.

105. From the above discussion, it can be seen that the evidence, largely does not support the historical assumption that the contact and fomite routes make a major contribution to the transmission of respiratory viral infections. Indeed, the authors of the two 2011 PIP reports on influenza (PIP-Team 2011a; PIP-Team 2011b) both concede this, with the *Respiratory and Hand Hygiene in an Influenza Pandemic* report, in particular, stating: ***"Since the role of hands in the transmission of influenza has actually never been demonstrated, one may hesitate to attribute a great proportion to this pathway"*** (PIP-Team 2011a). Therefore, with hindsight, it is surprising that at the start of the Covid-19 pandemic, the default assumption amongst the IPC and public health professionals was that the fomite and contact routes made a major contribution to SARS-CoV-2 transmission, while the airborne route was considered unlikely. Yet, the evidence in support of fomite/contact transmission was actually relatively weak, in comparison to that supporting the respiratory route (Andrewes & Glover 1941; Mubareka et al. 2009; PIP-Team 2011a). Indeed, the first confirmed epidemiological association between surface contamination and the transmission of SARS-CoV-2 did not emerge until 2023 (Derqui et al. 2023), just as the pandemic was ending.

Superspreading

Key findings:

- Superspreading is where many people become infected, often by only one person.
- Because superspreading is affected by the type of activity and the number of people present, as well as all the factors mentioned in earlier sections, it is best described as a superspreading event rather than a superspreading person.
- Many communal settings are likely to encourage superspreading, such as churches and nightclubs. Healthcare environments can also be affected by superspreading events.
- Superspreading events often involve music, singing or raised voices – activities that produce huge amounts of aerosol. There is also evidence that some infectious people who initiate superspreading events shed abnormally high viral loads.
- Covid-19 is prone to superspreading, with approximately 80% of onward transmission coming from 10-20% of infected people. In other words, transmission is "overdispersed", more so than with H1N1 influenza. Aerosol and asymptomatic transmission also make superspreading events more likely.

106. One important characteristic of the Covid-19 pandemic was superspreading, which is a term used when multiple people become infected at a single event, or by a single infectious person. Superspreading events often involve people who shed an abnormally high viral load (Goyal et al. 2021). However, this is only part of the story, because in order for the SARS-CoV-2 to be transmitted to multiple people an infectious person needs to come in to contact, or be in the proximity of multiple people in the relatively short window in which they are shedding a high viral load (Goyal et al. 2021). Therefore, superspreading events often occur in places where large numbers of people gather together in a confined space and talk loudly or sing, as evidenced by outbreaks at parties (Brandal et al. 2021), choir practices (Hamner et al. 2020; Miller et al. 2021); church services (James et al. 2020; Voeten et al. 2021); and in nightclubs (Jung et al. 2020). Places where music is played are particularly vulnerable to superspreading, because raised voices and singing associated with the exhalation of large numbers of respiratory aerosols (Alsved et al. 2020) and virus particles (Alsved et al. 2023a). For this reason, the term 'superspreading event' is generally used, because the extent to which superspreading can occur depends very much on the nature of the social event and the interactions that take place there.

107. Superspreading events play a key role in the transmission of respiratory viruses like SARS-CoV-2 amongst populations. This is because they act as hubs for the spread of infection within the community. Hundreds of people from a large urban area may congregate together in a church or nightclub for several hours, and if an infectious person is present, then a number of those who attend may contract an infection, which they will then take home and spread to others in their household. In this way, the virus can be spread rapidly through a community. The situation is made worse by the fact that when large numbers of people congregate together, it is more likely an infectious person will be present. It is even possible for multiple infectious people to be present at the same event if the number of people attending is high enough.

108. Superspreading was highly influential in driving the Covid-19 pandemic, with most cases infecting no one else, whereas, ***"propelled by superspreading events, 10% to 20% of cases cause***

80% of secondary infections" (Chen et al. 2021b) Epidemiologists call this phenomenon 'overdispersion', which broadly means that the transmission of SARS-CoV-2 is highly uneven, with superspreading playing a key role in driving the pandemic (Chen et al. 2021b; Wang et al. 2021b).

109. Because many superspreading events have happened in locations where singing occurs, or voices are raised (James et al. 2020; Miller et al. 2021; Voeten et al. 2021), it has caused some epidemiological modelers to suspect that aerosol transmission is implicated in many superspreading events (Chen et al. 2021a; Chen et al. 2021b; Goyal et al. 2021), with highly infectious individuals reportedly exhaling tens of thousands of virus particles per minute (Chen et al. 2021a). Indeed, with many superspreading events it is difficult to explain how transmission to large numbers of people could occur through the contact and fomite routes alone, whereas respiratory transmission appears to concur with observed transmission patterns (Chen et al. 2021b).

110. Superspreading of SARS-CoV-2 has also been observed within hospitals. For example, Illingworth et al. (Illingworth et al. 2021) found that 80% of transmission events in a Cambridge hospital caused by 21% of individuals. In particular, they found that patients were much more likely to be infected by other patients, rather than by HCWs. Patients also infected HCWs. This caused the authors to postulate that aerosol transmission might be occurring. While it is important to note that the presence of superspreading is not definitive proof of aerosol transmission, it does however make transmission by this route more likely. Accordingly, Illingworth et al. recommended that patients should wear face masks (even when they are in non-Covid green wards), and that ventilation of wards should be improved. In another nosocomial outbreak, airborne transmission of SARS-CoV-2 was strongly suspected in a superspreading event that occurred in Hong Kong hospital in which twelve patients and nine HCWs were involved (Cheng et al. 2021a). Also, in a Taiwanese hospital, a single index patients infected eight others (including four HCWs) with SARS-CoV-2 (Huang et al. 2022). The index patient was observed to frequently take off their face mask, which suggested that respiratory transmission might be involved. However, because of widespread environmental contamination of surfaces the authors concluded that fomite transmission was also likely to be involved.

111. Much SARS-CoV-2 transmission involves people who are asymptomatic or pre-symptomatic. However, the extent to which individuals without symptoms initiate superspreading events is less clear. While many Covid-19 superspreading events involve people with symptoms, cases have been reported where the superspreaders were either completely asymptomatic or pre-symptomatic at the time (Brainard et al. 2023; Groves 2021). Indeed, when specifically investigating this issue, Brainard et al. (Brainard et al. 2023) concluded that Covid-19 superspreaders often had very mild disease with minimal symptoms.

112. One notable feature of the Covid-19 pandemic is that transmission was highly over-dispersed in comparison to the 2009 H1N1 influenza pandemic (Chen et al. 2021b). This means that superspreading events were much more prominent in the former, compared with the latter. Although the reasons for this are not fully understood, it suggests that with SARS-CoV-2 greater variability exists in the viral load that is exhaled during breathing, talking, singing, etc., compared with H1N1 influenza (Chen et al. 2021a). From this, Chen et al (Chen et al. 2021a; Chen et al. 2021b) concluded that, while most people with Covid-19 exhale relatively low amounts of virus, a few infectious individuals shed a huge number of virus particles, and it is this that leads to potential superspreading events. By comparison, more H1N1 influenza cases are infectious, but shed virus particles at lower rates, hence more uniform transmission and fewer superspreading events.

Part 2: Historical controversy

113. In Part 2, the historical controversy that has persisted since the mid-twentieth century regarding the airborne transmission of respiratory infections is explained, and the ramifications of this on IPC policy investigated.

Misconceptions about respiratory transmission – the droplet and aerosol dichotomy

Key findings:

- Medical science and IPC practice has been beset by flawed assumptions about respiratory transmission for decades.
- These were namely that there were two types of respiratory transmission, droplet and aerosol. Some respiratory infections, such as influenza, were thought to transmit via droplets, whilst others such as TB, were thought to transmit via aerosols. Droplets and aerosols were defined as respiratory particles that are greater than or less than 5μm in diameter respectively.
- Those particles greater than 5μm, so-called “droplets”, were thought to travel no further than about 1.5 metres.
- The 5μm threshold became well embedded in the medical science literature and in IPC guidelines, with, for example, the 2-metre safe distance rule.
- Close-range transmission noted in epidemiological and animal studies was often wrongly thought to only be caused by larger droplets landing on the nose, mouth and eyes, instead of also being caused by the inhalation of near-field (and hence higher concentration) clouds of smaller aerosol particles.
- During the pandemic, the WHO and many other professional institutions relied on these flawed assumptions, despite some dissenting pre-pandemic evidence.
- Eventually the scientific evidence for airborne transmission of Covid-19, from studies using multiple types of methodology, became overwhelming (see Table 2) and the WHO acknowledged its significance with a change in official terminology adopted in 2024, reclassifying SARS-CoV-2 as a pathogen that is “transmitted through the air”. Many UK scientists, notably on the SAGE EMG subgroup, contributed significantly to these scientific advances and to public understanding of the science.
- The strengthening of the scientific evidence base about airborne transmission over the Covid-19 pandemic has huge implications for IPC policy and practice, covered further in parts 3 and 4 on PPE and ventilation.
- Physical science studies directly measuring aerosol particles have found that many so-called “Aerosol Generating Procedures” actually produce fewer aerosols than natural respiratory activities such as coughing.
- The 2011 Pandemic Influenza Preparedness (PIP) report was well-conducted and correctly identified the significant remaining uncertainty about influenza transmission. However, it also had several problems. Unlike many other studies it did acknowledge the risk of airborne transmission, but only at close range, and made an important flawed assumption about large droplets conferring most of the infection risk due to their volume.
- Despite its nuanced and uncertain conclusions, the limited evidence base and key assumptions provided in the PIP report made their way into definitive guidelines that, during an influenza pandemic (and by extension other respiratory virus pandemics), restricted respirators to only staff conducting AGPs on influenza patients. Newer evidence that large amounts of virus could be naturally exhaled by infectious patients did not shift this initial policy choice during the Covid-19 pandemic.

114. In this section, an overview is given of the historical controversy that has surrounded the airborne transmission of infectious disease, together with an explanation of how incorrect thinking regarding the behaviour of aerosolized respiratory particles shaped policy in this area. Here the focus is on the science rather than on specific policies, which are discussed in more detail in the UK Covid-19 Inquiry's clinical expert report by Professor Dinah Gould, Dr Ben Warne, and Dr Gee Yen Shin.

115. Many medical and IPC professionals have misconceptions regarding the nature and behaviour of infectious respiratory aerosols. These misconceptions are historical, widely accepted and often repeated in medical textbooks and in scientific papers, despite being factually incorrect. Nonetheless, they have been extremely influential and over many years have shaped policy in this area. This has led to much of the confusion, especially regarding the terminology that has traditionally been used in IPC guidelines to describe the transmission of respiratory viral infections, which has not kept pace with the significant advances in science that occurred during the Covid-19 pandemic (WHO 2024b).

116. When discussing this issue in the context of Covid-19, a useful frame of reference is the 23rd December 2021, which is the date on which the WHO finally changed its stance (there was partial acceptance on 30th April 2021) and accepted that SARS-CoV-2 could be transmitted via aerosol particles that can remain suspended in air and travel further than 2 meters (Lewis 2022; Morawska et al. 2023). Prior to this date, the WHO were at pains to stress that Covid-19 was not an airborne disease (Beggs 2020)*, even going as far as to Tweet on 28th March 2020***: "FACT: #COVID19 is NOT airborne …"*** (Lewis 2022). However, after this date, as scientific evidence accumulated, the WHO's stance progressively changed to one that considered the airborne transmission of SARS-CoV-2 to be a major problem. This ultimately led to the WHO partnering with the Conseil Européen pour la Recherche Nucléaire (CERN) to develop a tool for assessing the risk of airborne SARS-CoV-2 transmission indoors (WHO 2024b), and convening a high-level technical consultation group to attempt to correct some of the historical misconception surround transmission of viral pathogens through the air (WHO 2024a). However, while a clear transformation took place in the WHO's thinking in December 2021, there was some regret that it did not happen earlier. In an interview published in the journal *Science* on 23rd November 2022, Dr Soumya Swaminathan, the WHO's retiring chief scientist, publicly stated that her biggest regret was not acknowledging early in the pandemic that SARS-CoV-2 could be spread by aerosols (Kupferschmidt 2022).

117. The change in the WHO's stance primarily came about because of overwhelming evidence presented to them by eminent scientists, clinicians and engineers from around the world, who profoundly disagreed with the consensus held by the medical community regarding the airborne transmission of infectious disease (see (Lewis 2022; Morawska et al. 2023; Tang et al. 2021a) for full details). While this disagreement reached its culmination during the Covid-19 pandemic, the truth is that the controversy actually began early in the 20th century (Molteni 2021), and still persists today (August 2024), with scientific debate ongoing about the terminology that should be used to describe the transmission of pathogens through the air (Greenhalgh et al. 2024b; WHO 2024a). Terms like droplet, aerosol and airborne transmission are frequently used in guidance documents, but because there is ambiguity and confusion as to what actually constitutes a droplet or an aerosol, many inconsistencies and misconceptions persist.

118. While the historical controversy surrounding droplets and aerosols might appear rather academic, in reality, the misconceptions held by the medical community on this subject had a far-reaching impact on the preparedness of the UK and the world for the Covid-19 pandemic, as well as on

the IPC measures adopted and the PPE used. This is because respiratory viruses such as influenza and SARS-CoV-2 were deemed not to be transmitted by the airborne route, with the result that the IPC advice issued in the UK (and overseas) during 2020 and much of 2021 focused on prevention of SARS-CoV-2 transmission via the droplet, contact and fomite routes, rather than through aerosols (i.e., airborne transmission).

119. As outlined above, any discussion of Covid-19 needs to be viewed in the context of the historical demarcation between droplet and airborne transmission of infectious disease that persisted long before the pandemic. This wrongly asserted that: **"*Droplets are large particles (5µm or larger) that rapidly settle out on horizontal surfaces; thus they are not transmitted beyond a radius of several feet from the source*"** (Ayliffe et al. 1982), as illustrated in Figure 11 (reproduced from (Tabatabaeizadeh 2021)). Indeed, the 5µm cut-off threshold became ingrained into the medical literature, with the WHO's 2014 guidance *'Infection prevention and control of epidemic- and pandemic-prone acute respiratory infections in health care'*, specifically using it to define the difference between 'droplets', which were not considered to be airborne, and 'droplet nuclei' which were airborne (WHO 2014). However, 5µm threshold is not consistent with the physics of droplets and aerosols (Randall et al. 2021). In fact, as Table 1 shows, respiratory particles as large as 20µm in diameter are so light that they can remain suspended in air for over two minutes. This means that particles in the size range 5µm to 20µm (perhaps even up to 30µm) can remain suspended in air and be transported several meters, or more (i.e., much further than 2 meters), depending on the strength the exhalation (i.e., cough verses talking) (Bourouiba 2020; Randall et al. 2021) and the room air currents (Obeid et al. 2023; Xie et al. 2007). As such, particles in this size range are aerosols and not droplets. By definition, droplets behave ballistically (like a stone being thrown) and cannot be suspended in air, which is completely different to the behaviour of aerosol particles up to 20µm diameter. When exhaled, all respiratory particles <100µm rapidly evaporate to become small aerosol particles which can become suspended in air, as Wells demonstrated in the 1930s (Wells 1934; Xie et al. 2007). Such particles generally evaporate to about a third of their original size in less than a second. Only, those respiratory particles >100µm diameter cannot evaporate fully before they reach the floor (Wells 1934; Xie et al. 2007). These are true droplets that behave ballistically, and so cannot be projected further than about 1.5 metres. So, from an aerodynamic standpoint, the 5µm droplet threshold stated above, is completely nonsensical because particles >5µm diameter: (i) are not droplets; (ii) do not behave like droplets; and (iii) can travel much further than 2 metres. For exhaled respiratory particles, a much better droplet/aerosol threshold is 100µm, as many have suggested (Tang et al. 2021a; Wei & Li 2015; Wells 1934; Wells 1955; Xie et al. 2007).

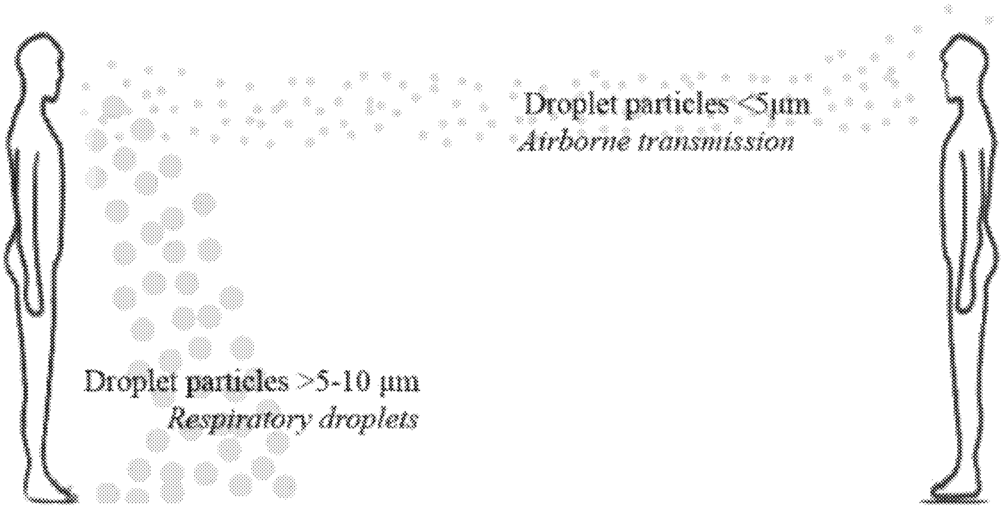


Figure 11. Historical dichotomous model of respiratory transmission, which incorrectly defines particles greater than 5µm diameter as "droplets" and assumes that these behave ballistically and fall rapidly to the ground (Tabatabaeizadeh 2021). In reality, there are not two types but a spectrum of respiratory particle sizes, see Figure 1.

120. Comparison between Figure 1, which reflects the state-of-the-art physical science, and Figure 11, which summarises the historical, but incorrect, model of respiratory transmission, reveals that the two look superficially similar. The crucial difference however, is that in Figure 11, all the viral material contained in particles >5µm diameter is incorrectly assumed to fall rapidly to the floor within about 1.5 meters from the infectious person, whereas in Figure 1, all but the largest particles (>100µm before evaporation), behave as aerosol particles of various sizes that can potentially be transported in air currents and be inhaled.

121. While Wells' meticulous work on droplet evaporation was embraced by the physics, engineering and aerosol science communities, it was largely overlooked, or misinterpreted by many in the medical community (Lewis 2022; Molteni 2021; Morawska et al. 2023; Tang et al. 2021a). This in part was because Wells showed that TB is caused by the inhalation of small infectious respiratory particles <5µm diameter (which he called '**droplet nuclei**') that penetrate deep into the lungs (Wells 1955). Being so small, these droplet nuclei, when exhaled, became truly airborne and could travel considerable distances (hence the term 'airborne' transmission). Unfortunately, from this the medical community erroneous concluded that because droplet nuclei are airborne, it must therefore mean that all other respiratory particles >5µm behave like droplets and cannot become airborne (hence the term 'droplet' transmission). From this, the 5µm droplet/droplet nuclei threshold emerged and quickly became set in stone, being taught to generations of medical students, despite being deeply flawed.

122. One of the unintended consequences of the inappropriate 5µm threshold, was that scientists from different disciplines used completely different terms to describe the same objects. So, for example, a 12µm diameter respiratory particle might be called a droplet by clinicians and

microbiologists, whereas the same object would be an aerosol particle to an engineer or physicist. However, while both groups might be talking about the same object, the former would assume (erroneously) that the particle would behave ballistically, rapidly falling to the floor and not travel further than about 1.5m, whereas the latter would correctly assume that the particle could be suspended in air and be able to travel considerable distances. Over the years, this bizarre situation led to much needless argument, contention and confusion (which is still ongoing (Greenhalgh et al. 2024b; WHO 2024a)), which obscured things and led to positions becoming entrenched.

123. Notwithstanding the discussion above, from a medical standpoint there were good clinical reasons for using the 5μm threshold. Respiratory particles >5μm diameter generally impact in the upper respiratory tract (i.e., the nasopharyngeal region), whereas smaller particles <5μm can travel deep into the lungs (i.e., down to the alveoli) (Atkinson et al. 2009). This demarcation fitted the clinical evidence. The site of infection for influenza and the common cold is generally the upper respiratory tract, and therefore these were presumed to be caused by infectious particles >5μm, whereas TB infections occur deeper in the lungs, were only infectious particles <5μm can reach. This is the reason why the 5μm threshold persisted for so long in medical textbooks, and in the thinking of medical professionals, as illustrated in the WHO's 2009 guidance document *'Natural Ventilation for Infection Control in Health-Care Settings: Annex C'* (Atkinson et al. 2009). However, while the 5μm droplet/droplet nuclei threshold appeared to make sense clinically, from the point of view of physics this demarcation was deeply flawed.

124. Another erroneous long-standing assumption, which appeared reasonable at the time, was the belief that infectious material (i.e., viruses and bacteria) are evenly distributed throughout the entire volume of any respiratory particles that are exhaled. This meant that it was historically assumed that the vast majority (i.e., about 99%) of viruses were contained in larger particles >10μm diameter (Nicas et al. 2005; PIP-Team 2011b; Weber & Stilianakis 2008), which being thought of as 'droplets', were (incorrectly) assumed to travel no further than about 1.5m. Consequently, it was assumed (wrongly) that the viral load in inhalable aerosols must therefore be very low (about 1% according to (PIP-Team 2011b)). However, this assumption now appears incorrect, as numerous studies involving SARS-CoV-2 (Alsved et al. 2023a; Coleman et al. 2022; Jaumdally et al. 2024; Tan et al. 2023) and influenza (Bischoff et al. 2013; Coleman & Sigler 2020; Lindsley et al. 2010b; Yan et al. 2018) patients have now shown that the smallest respiratory particles <5μm diameter are the ones that contain most of the viral load. This suggests that the viruses are unevenly distributed in exhaled respiratory particles with most virus particles found in the smallest aerosols rather than the larger droplets. As such, this finding has huge implications, because it undermines the argument that Covid-19 and influenza are primarily droplet-borne diseases, and questions the assumptions on this subjects made in pandemic preparedness guidance issued by the NHS (HPIH&SD_PIP 2009; PIP-Team 2011b) and the WHO (WHO 2014).

125. One of long-standing problem that has plagued research in this field, has been an inability in epidemiological and animal studies to distinguish between droplet and aerosol transmission. For example, numerous animal studies involving ferrets and guinea pigs have shown that influenza can be transmitted by particles that pass through the air (Belser et al. 2022; Mubareka et al. 2009; Richard et al. 2020; Sutton et al. 2014). However, it is not known to what extent this is by droplets or aerosols. Given this doubt, researchers have tended to fall back on the *a priori* assumption that the vast majority of the exhaled viral load is in the larger droplets, and thus concluded that transmission is much more likely to be by the droplet route, rather than via aerosols (PIP-Team 2011b). **However, if the *a priori* assumption is that most of the virus is contained in the small aerosols, then this would lead to a completely different interpretation of the**

evidence, and point to aerosol transmission being the more likely route, as the results of several animal studies have strongly indicated (Andrewes & Glover 1941; Kutter et al. 2021).

126. All too often, short-range transmission has been historically assumed to be evidence of droplet transmission. Yet, this overlooks the more likely possibility that near-field aerosol transmission might actually be occurring (see paragraphs 75 to 85). This is because the concentration of infectious aerosols exhaled is always highest closest to the source. Therefore, someone located <2 meters in front (i.e., in the near-field) of an infectious person is likely to be exposed to a high aerosol concentration from the hosts exhalation plume, as shown in Figure 1. So, as Prof. Don Milton stated, when giving evidence to the CDC: ***"it is now widely recognized that the traditional notion that close proximity equals transmission via sprays of ballistic drops called "droplet transmission" (is) wrong"*** (CDC 2023a).

127. From the discussion above, it can be seen that misconceptions that took hold in the twentieth century, became influential and shaped much IPC thinking. Indeed, they became so ingrained, that a mindset developed that was highly resistant to new ideas from other disciplines. This manifested itself during the Covid-19 pandemic when there was great opposition from the WHO and others to the suggestion that SARS-CoV-2 might be transmitted by the airborne route (Lewis 2022; Molteni 2021; Morawska et al. 2023). **The reasons for this were primarily due to *a priori* assumptions about the routes involved in SARS-CoV-2 transmission (which did not include airborne transmission), despite the evidence supporting these assumptions being relatively weak and understanding of the associated physical science being flawed** (PIP-Team 2011a; PIP-Team 2011b)**.** The situation was also not helped by disputes over the terminology that should be used (Greenhalgh et al. 2024b; Tang et al. 2021a), and the rigid categories in the medical literature used to classifying infectious diseases (i.e., blood-borne, hand-borne, droplet-borne and airborne), which do not reflect the complexity of physical science. Consequently, many long-standing misconceptions persisted into the Covid-19 pandemic, some of which still need to be resolved.

Shift in the scientific consensus

128. In this section we explore the shift in scientific consensus regarding the transmission of SARS-CoV-2 that occurred during the Covid-19 pandemic. Although some UK scientists played a very influential role in this, because of the international nature of the work discussed, this section is largely written within the framework of the change in thinking that occurred within the WHO.

129. Prior the Covid-19 pandemic and up to 23rd December 2021 (when the WHO softened its stance on airborne transmission of SARS-CoV-2), the scientific consensus amongst the medical community (but **not** amongst physicists and engineers) was that SARS-CoV-2 and influenza were not airborne, but rather, transmitted via droplets and by various contact routes (HPIH&SD_PIP 2009; WHO 2014; WHO 2020). Only a few infectious diseases (i.e., TB, measles and chickenpox) were deemed to be transmitted by the airborne route, which were classified by the WHO as being via infectious particles <5μm diameter (WHO 2020), and this was reflected in both WHO (Atkinson et al. 2009) and NHS (DoH 2013) guidance on the ventilation of healthcare facilities.

130. At the start of the Covid-19 pandemic the 5μm droplet/droplet nuclei threshold was widely accepted by the WHO, CDC and most IPC professionals in the UK and globally. However, as evidence started to emerge (see Table 2 below for details of key scientific papers) that SARS-CoV-2 could be transmitted by the airborne route it was gradually realised that this threshold was incorrect and not fit for purpose (Morawska et al. 2023; Prather et al. 2020a; Tang et al. 2021a).

So, the consensus shifted and was gradually replaced with a looser droplet/aerosol threshold, with droplets defined as being larger than 100µm diameter, and aerosols being the smaller respiratory particles that are produced when droplets <100µm evaporate, which was more in line with Well's original work conducted in the 1930s (Wells 1934; Xie et al. 2007). However, while 100µm is becoming widely accepted as the droplet/aerosol threshold, there is still resistance by some in the medical community to this, and so the scientific debate is still ongoing about the correct terminology that should be used in this context (Greenhalgh et al. 2024b; WHO 2024a).

131. The change in the WHO's position from Covid-19 **'not being airborne'** to **'being airborne'** was not sudden, but rather a gradual transition that occurred at multiple levels as more and more evidence accumulated. Furthermore, rather than purely being a UK affair, this transition took place at a global level, with leading UK scientists and clinicians (e.g., Prof. Catherine Noakes, Prof. Stephanie Dancer, Prof. Julian Tang, Prof. Trisha Greenhalgh, etc.) working closely with colleagues overseas (e.g., Prof. Lidia Morawska, Prof. Don Milton, Prof. Shelly Miller, etc.) on multiple projects related to the transmission of SARS-CoV-2. **Importantly, the transition was largely driven by the involvement of physicists, engineers and aerosol scientists who took a broader multidisciplinary approach to understanding SARS-CoV-2 transmission, compared with that previously taken.**

132. Table 2 sets out the dates of key scientific publications (January 2020 to June 2022) that shifted the weight of evidence regarding the transmission of Covid-19 from the initially assumed droplet transmission, towards airborne transmission. Early in the pandemic (April, May, June, July 2020) Morawska and colleagues (Morawska & Cao 2020; Morawska & Milton 2020), Li (Li et al. 2020), Bourouiba (Bourouiba 2020) and Beggs (Beggs 2020)* published articles warning that SARS-CoV-2 transmission was likely to be airborne. Others produced evidence to show that: SARS-CoV-2 could survive for hours in aerosols and on surfaces (Van Doremalen et al. 2020b); surgical mask significantly reduced the viral load in aerosols exhaled by people infected with human coronavirus (Leung et al. 2020); SARS-CoV-2 RNA could be isolated from the air in hospitals (Liu et al. 2020b; Santarpia et al. 2020a); large numbers of respirable aerosol particles were exhaled during breathing, talking and singing, and that these greatly increased in number with loudness (Alsved et al. 2020); and that the risk of infection diminished as the room ventilation rate increased (Buonanno et al. 2020). However, it was not until Miller et al. (Miller et al. 2021) published epidemiological analysis of the Skagit Valley Chorale superspreading event (published online in September 2020) that the idea that SARS-CoV-2 might be airborne started to gain wider traction.

133. From this we see that before the second Covid-19 wave (which started in the UK in September 2020) there was growing body of evidence to suggest that Covid-19 is an airborne disease. In particular, epidemiological evidence from the Skagit Valley Chorale superspreading event (Hamner et al. 2020; Miller et al. 2021)) and the Covid-19 outbreak that occurred in a restaurant in Guangzhou, China (Li et al. 2021), strongly implicated far-field aerosol transmission. Furthermore, there was plenty of robust evidence to indicate that transmission of SARS-CoV-2 by the aerosol route was plausible (Leung et al. 2020; Liu et al. 2020a; Ong et al. 2020; Santarpia et al. 2020b; Van Doremalen et al. 2020b), especially when voices are raised (Alsved et al. 2020). This evidence, coupled with pre-Covid-19 knowledge of the potential aerosol transmission of influenza (Bischoff et al. 2013; Lindsley et al. 2010b; Moser et al. 1979; PIP-Team 2011b; Tellier 2009; Yan et al. 2018), gave good reason to believe that SARS-CoV-2 transmission might be occurring by the aerosol route. The findings of Nissen et al (Nissen et al. 2020) (published 11th November 2020) reinforced this opinion, when they demonstrated long-range (>40 metres) transmission of RNA in aerosols containing SARS-CoV-2 RNA in a central ventilation system in a Swedish hospital.

134. Having said this, two studies published during the second Covid-19 wave were somewhat ambiguous and less supportive of the airborne transmission of SARS-CoV-2. The first, a systematic review by Comber et al. (Comber et al. 2020) (published on 26th October 2020) is interesting because it found that ***"seven out of eight epidemiological studies suggest aerosol transmission may occur, with enclosed environments and poor ventilation noted as possible contextual factors".*** From which they concluded that although aerosol transmission of SARS-CoV-2 may be occurring, the overall evidence was inconclusive regarding the viability and infectivity of SARS-CoV-2 in aerosols. Accordingly, they reported that there was considerable uncertainty concerning the contribution that aerosols make to the spread of SARS-CoV-2, relative to other routes of transmission. In the second study by Moore et al. (Moore et al. 2021) (published 28th November 2020), SARS-CoV-2 RNA was recovered in low concentrations from the air around hospital patients. This led the authors to conclude that it was likely that the virus was not viable and that far-field aerosol transmission was therefore probably not occurring. Notwithstanding this, Moore et al. (Moore et al. 2021) did not exclude the possibility that short-range aerosol transmission might be occurring, and recommended that current PPE guidance, which required HCWs to wear respirator masks and face visors, be followed when undertaking 'aerosol generating procedures' (AGPs).

135. In April 2021, a large systematic review with meta-analysis was published by Chen et al. (Chen et al. 2021a) which strongly implicated respiratory aerosols in the overdispersion (superspreading) that characterised the Covid-19 pandemic. The authors concluded that aerosolization during breathing, talking and singing by those with a high viral load in their respiratory tract was probably responsible for many superspreading events.

136. In August 2021, an influential laboratory study by Coleman et al (Coleman et al. 2022) produced strong evidence that SARS-CoV-2 could be transmitted in exhaled aerosols and that this might be a widespread phenomenon. They found that 59% of the study participants (n = 23) emitted detectable levels of SARS-CoV-2 RNA in exhaled respiratory aerosols. Furthermore, they found observed 85% of the RNA exhaled by the Covid-19 patients was contained in small aerosol particles <5μm diameter. This is was a very important finding because it showed for the first time that the virus was most likely to be found in small aerosols that can travel long distances, rather than in the large droplets that quickly fall to the ground. As such, this finding undermined previous assumptions that the bulk of virus particles are most likely to be found in larger droplets (PIP-Team 2011b; Weber & Stilianakis 2008).

137. Other influential studies published after the second Covid-19 wave in the UK, were Illingworth et al. (Illingworth et al. 2021), Conway Morris et al. (Conway Morris et al. 2021a; Conway Morris et al. 2021b) and Cooper et al. (Cooper et al. 2021; Cooper et al. 2023), which appeared as preprints in August, September and November 2021, respectively. Illingworth et al. (Illingworth et al. 2021) found superspreading to be a characteristic of SARS-CoV-2 transmission in hospitals, with 80% of transmission events in a Cambridge hospital caused by 21% of individuals. In particular, the authors of this study highlighted the importance of inpatients wearing face masks and good ward ventilation to reduce the risk of aerosol dispersal. In the second study, Conway Morris et al. (Conway Morris et al. 2021a; Conway Morris et al. 2021b) showed that lower levels of SARS-CoV-2 RNA in the hospital ward air were associated with the use of supplementary high efficiency particulate air (HEPA) filter air cleaners. In the third study, which involved analysis of data collected between June 2020 and March 2021 from 145 acute hospitals in England, Cooper et al. (Cooper et al. 2021; Cooper et al. 2023) concluded that there was good evidence that both asymptomatic and airborne transmission were contributing to the burden of Covid-19 in NHS hospitals.

138. Other papers that were influential were: Johansson et al. (published in January 2021) (Johansson et al. 2021) who estimated that more than half of SARS-CoV-2 infections originated from exposure to asymptomatic people who had no symptoms; and Brandal et al. (published December 2021) (Brandal et al. 2021) who reported on an early Omicron superspreading event, which occurred in an Oslo restaurant when 74% of guests at a party became infected. These papers are important because they respectively highlighted: (i) the large amount of asymptomatic transmission that was occurring; and (ii) the ease with Omicron could be transmitted to large numbers of people – something, although not confirmed, is consistent with airborne transmission, as some have suggested (Cheng et al. 2022).

139. **Collectively, the weight of evidence presented above, indicates that by the end of September 2020 there was enough moderate certainty evidence to strongly suggest that SARS-CoV-2 could be transmitted via the airborne route (i.e., in naturally exhaled aerosols, not produced during AGPs), and to justify precautionary measures being taken by health authorities to prevent this route of transmission in hospitals and elsewhere.** Indeed, by December 2021 (when the WHO acknowledged that the airborne transmission of SARS-CoV-2 was likely occurring) there was good high certainty evidence to believe that aerosol transmission was substantially contributing to the burden of Covid-19 in the NHS. This opinion further crystallised when Duval et al. (Duval et al. 2022), in a systematic review published in June 2022, found firm epidemiological evidence to suggest that the far-field aerosol transmission of SARS-CoV-2 was occurring.

Table 2. Key scientific papers assessing airborne transmission of Covid-19 published during the period January 2020 to June 2022 (the relevant period of Module 3 of the UK Covid-19 Inquiry).

Date**	Publication as preprint and/or journal paper	Advance
4th March 2020	Ong et al. (Ong et al. 2020)	Found SARS-CoV-2 RNA on air exhaust outlets in Covid-19 patient rooms and concluded that aerosol transport of the virus might be occurring.
10th March 2020	Liu et al. (Liu et al. 2020a; Liu et al. 2020b)	Found SARS-CoV-2 RNA in the air in a hospital in Wuhan, China. (As of June 2024, cited over 2,300 times according to Google scholar.)
17th March 2020	Van Doremalen et al. (Van Doremalen et al. 2020b)	Showed the SARS-CoV-2 could survive for hours on surfaces and in the air. (As of June 2024, cited over 12,800 times according to Google scholar.)
26th March 2020	Bourouiba (Bourouiba 2020)	Showed that aerosols and droplets could be projected up to 8 metres in a turbulent gas cloud when sneezing and coughing. (As of June 2024, cited over 1,700 times according to Google scholar.)
26th March 2020	Santarpia et al. (Santarpia et al. 2020a; Santarpia et al. 2020b)	Found SARS-CoV-2 RNA in the air in the rooms of Covid-19 patients in a USA hospital. Concluded that SARS-CoV-2 was being transported around the hospital in aerosols. (As of June 2024, cited over 600 times according to Google scholar.)

2nd April 2020	Lewis (Lewis 2020)	An article published in Nature, which highlighted a warning from Prof. Lidia Morawska that: “**there's absolutely no doubt that the (SARS-CoV-2) virus spreads in the air”.** The article also highlights the fundamental disagreement between the WHO and Prof. Morawska (and her colleagues around the world) regarding whether or not Covid-19 is an airborne disease.
3rd April 2020	Leung et al. (Leung et al. 2020)	Using data gathered before the Covid-19 pandemic, found seasonal human coronaviruses, influenza and rhinovirus in exhaled breath and coughs of infected children and adults. Showed that surgical masks significantly reduced detection of coronavirus RNA in aerosols. (As of June 2024, cited over 2,600 times according to Google scholar.)
10th April 2020	Morawska & Cao (Morawska & Cao 2020)	An influential narrative review (as of June 2024, cited over 2,000 times according to Google scholar) which warned that Covid-19 was an airborne disease driven by transmission indoors. It summarised what was known about the physical mechanisms of transmission before the pandemic, and epidemiological evidence from the SARS epidemic, arguing that in emerging evidence about Covid-19 spread, justified implementing control measures against airborne transmission.
22nd April 2020	Li et al. (Li et al. 2021; Li et al. 2020)	Reported evidence of aerosol transmission of SARS-CoV-2 in a poorly ventilated restaurant in China. (As of June 2024, cited over 400 times according to Google scholar.)
15th May 2020	Hamner et al. (Hamner et al. 2020)	The first epidemiological report of the Skagit Valley Chorale outbreak. Considered that aerosol, droplet and fomite transmission were all possible and highlighted the increased risk of aerosolization from singing. (As of June 2024, cited over 900 times according to Google scholar.)
26th May 2020	Beggs (Beggs 2020)*	Warned that the WHO 5µm droplet/droplet nuclei threshold was not fit for purpose and explained that infectious respiratory aerosols of various sizes could remain airborne for considerable periods of time.
27th May 2020	Morawska et al. (Morawska et al. 2020)	Explained how improved room ventilation could help to reduce the risk of acquiring Covid-19.
4th June 2020	SAGE EMG (SAGE-EMG 2020e)	SAGE Environmental Modelling Group paper; *“Transmission of SARS-CoV-2 and mitigating measures”*. This report concluded that droplet and fomite transmission were probably the most important routes of transmission. However, it also noted that there was weak evidence for the aerosol

		transmission under poorly ventilated conditions (see paragraph 130).
6th July 2020	Morawska & Milton (Morawska & Milton 2020)	A high-profile open letter signed by 239 scientists from around the world, warning that Covid-19 was an airborne disease and that infectious aerosols could pose a risk at distances beyond 2 metres.
22nd July 2020	SAGE NERVTAG & EMG (SAGE-EMG 2020b)	SAGE Environmental Modelling Group and NERVTAG joint paper "Role of Aerosol Transmission in Covid-19". This report highlighted the possibility that SARS-CoV-2 might be transmitted in respiratory aerosols, and concluded that aerosol transmission was most likely to occur within 2 metres. However, the evidence was not deemed sufficiently strong to recommend the use of FFP3 respirators by HCWs, other than when AGPs were being conducted (see paragraph 130).
6th September 2020	Buonanno et al. (Buonanno et al. 2020)	Developed a method for quantifying the risk of acquiring a Covid-19 via the airborne route. The authors showed that the risk diminished as the room ventilation rate increased. (As of June 2024, cited over 400 times according to Google scholar.)
17th September 2020	Alsved et al. (Alsved et al. 2020)	Quantified the number of respiratory aerosol particles exhaled during breathing, talking and singing, and conclusively showed that the numbers produced greatly increased with loudness. (As of June 2024, cited over 200 times according to Google scholar.)
26th September 2020	Miller (Miller et al. 2021)	Performed further epidemiological analysis of the Skagit Valley Chorale superspreading event. Concluded that there was overwhelming evidence of long-range (far-field) airborne transmission and that fomite or ballistic droplet transmission was unlikely to explain a substantial fraction of cases. Modelled the effect of shortening exposure time and increasing ventilation to reduce the risk of outbreaks. (As of June 2024, cited over 700 times according to Google scholar.)
30th September 2020	SAGE EMG (SAGE-EMG 2020c)	SAGE Environmental Modelling Group paper "Role of ventilation in controlling SARS-CoV-2 transmission". This report acknowledged that far-field (>2 metres) aerosol transmission of SARS-CoV-2 can occur, and highlighted the importance of good ventilation to mitigate spread via this route (see paragraph 130).
5th October 2020	Prather et al. (Prather et al. 2020a)	Highlighted the 100µm droplet/aerosol threshold and clearly stated that aerosols contain particles of various sizes that are all <100µm diameter.

26th October 2020	Comber et al. (Comber et al. 2020)	In this systematic review the authors concluded that there was some evidence to suggest that SARS-CoV-2 may be transmitted in aerosols. However, there was considerable uncertainty concerning the contribution that aerosols make, relative to other routes of transmission.
11th November 2020	Nissen et al. (Nissen et al. 2020)	In this case study conducted in a Swedish hospital the authors were able to demonstrate that aerosols containing SARS-CoV-2 RNA were travelling >40 metres along ducts in a central ventilation system.
13th January 2021	Tang et al. (Tang et al. 2021a)	Explained why many of the long-standing assumptions in the medical community regarding the airborne transmission of infection are incorrect, and highlighted why the 100µm droplet/aerosol threshold was correct. (As of June 2024, cited over 300 times according to Google scholar.)
13th January 2021	SAGE EMG (SAGE-EMG 2021)	SAGE Environmental Modelling Group paper "Application of physical distancing and fabric face coverings in mitigating the B117 variant SARS-CoV-2 virus in public, workplace and community". This report accepted that far-field (>2 metres) aerosol transmission of SARS-CoV-2 can occur, and proposed a superior size classification system that more realistically reflected the true behaviour of exhaled respiratory particles (see paragraph 130).
15th April 2021	Greenhalgh et al. (Greenhalgh et al. 2021)	Highlighted many of the flawed assumptions made by the medical community, and presented multidisciplinary evidence that SARS-CoV-2 was transmitted in aerosols.
16th April 2021	Chen et al. (Chen et al. 2021a)	Large systematic review with meta-analysis which demonstrated that superspreading (overdispersion) of SARS-CoV-2 is associated with the exhalation of a high viral load in >100µm droplets and <100µm aerosols by a few individuals.
25th March 2021	SAGE HOCI & EMG (SAGE-HOCI 2021)	SAGE Hospital Onset Covid-19 Infection Group and Environmental Modelling Group joint paper "Masks for healthcare workers to mitigate airborne transmission of SARS-CoV-2". This report stressed the need for a hierarchy of controls, including good ventilation, that must be undertaken first, rather than relying on PPE (including surgical masks) to provide protection. FFP3 respirators were only deemed necessary for those performing AGPs.
6th August 2021	Coleman et al. (Coleman et al. 2022)	Demonstrated that 85% of the SARS-CoV-2 RNA exhaled by Covid-19 patients is contained in aerosol particles <5µm. (As of June 2024, cited over 100 times according to Google scholar.)

24th August 2021	Illingworth et al. (Illingworth et al. 2021)	Found superspreading to be a characteristic of SARS-CoV-2 transmission in hospitals, with 80% of transmission events in a Cambridge hospital caused by 21% of individuals. Highlighted the importance of ventilation and inpatients wearing face masks to reduce the risk of aerosol dispersal.
22nd September 2021	Conway Morris et al. (Conway Morris et al. 2021a; Conway Morris et al. 2021b)	Showed that the use of supplementary HEPA filter air cleaning devices on a hospital ward is associated with greatly reduced SARS-CoV-2 RNA levels in the air.
30th November 2021	Cooper et al. (Cooper et al. 2021; Cooper et al. 2023)	In a large survey of data from 145 acute hospitals in England, the authors concluded that there was good evidence in support of: (i) asymptomatic; and (ii) airborne, transmission contributing to the burden of Covid-19 in NHS healthcare facilities. Preprint published in November 2021, but eventually published in Nature on 18th October 2023.
16th December 2021	Brandal et al. (Brandal et al. 2021)	First report of an Omicron superspreading event in which 74% of the attendees at a party in a Norwegian restaurant acquired a Covid-19 infection, despite many being some distance from the index case. Although the authors make no mention of airborne transmission, other subsequent researchers showed that this was likely to be occurring (Cheng et al. 2022).
9th June 2022	Prentiss et al. (Prentiss et al. 2022)	Quantified the expected viral dose that needs to be inhaled in order to contract Covid-19 via the airborne route.
29th June 2022	Duval et al. (Duval et al. 2022)	First systematic review of the epidemiological evidence to suggest that long distance (far-field) transmission of SARS-CoV-2 can occur in aerosols.

* Clive Beggs is the author of this paper.

** Date of first online publication either as pre-print or as journal article.

Scientific consensus in the UK

140. In the UK, thanks to the work of Professor Catherine Noakes, the Scientific Advisory Group for Emergencies (SAGE) was aware from 14th April 2020 (when Prof. Noakes gave a presentation to SAGE) that the transmission of SARS-CoV-2 might be occurring through the airborne route [Prof. Noakes witness statement - INQ000236261]. Consequently, Prof. Noakes was asked to form and chair a new multidisciplinary sub-group within SAGE to respond to specific questions regarding the transmission of SARS-CoV-2. This group became the Environmental and Modelling Group (EMG), whose primary focus was the transmission mechanisms and mitigation of the virus in enclosed (mostly indoor) environments. As such, the EMG was influential in evaluating the scientific evidence as it emerged and advising SAGE and the UK Government on matters relating to the physical science associated with SARS-CoV-2 transmission. In particular, it produced a

number of useful guidance documents, which amongst other things, informed IPC policy in the NHS during the pandemic.

141. For brevity we summarize here a few key documents produced by the SAGE EMG sub-group which highlight how the scientific narrative changed as more and more evidence emerged during the pandemic.

- **'Transmission of SARS-CoV-2 and mitigating measures'** (published on 4th June 2020) (SAGE-EMG 2020e): This report concluded that droplet and fomite transmission were probably the most important routes of transmission. However, it was also noted that: ***"There is weak evidence that aerosol transmission may play a role under some conditions such as in poorly ventilated crowded environments."*** Evidence of asymptomatic transmission and the emergence of superspreading events was also noted.

- **'Role of aerosol transmission in COVID-19'** (published on 22nd July 2020) (SAGE-EMG 2020b): This document reflected increased interest in the airborne transmission of SARS-CoV-2, and highlighted the possibility that the virus might be transmitted in respiratory aerosols. The report concluded that aerosol transmission was most likely to occur within 2 metres, but felt that the evidence was not strong enough to recommend the use of fit-tested FFP3 respirators, other than in situations where AGPs were being conducted. Importantly, the report defined droplets as being >10µm, but did not say that these behaved ballistically. Rather, they stated that these ***"will normally settle out of the air in less than 5 minutes"***, which is scientifically correct (see Table 1). In so doing, the EMG demonstrated a superior understanding of the physics of droplets and aerosols, compared with statements made in many other publications (e.g., (Ayliffe et al. 1982; NHS-Scotland 2024a; PIP-Team 2011b; Tabatabaeizadeh 2021)).

- **'Role of ventilation in controlling SARS-CoV-2 transmission'** (Published on 30th September 2020 (SAGE-EMG 2020c): This report acknowledged that far-field (>2 metres) aerosol transmission of SARS-CoV-2 can occur, and highlighted the importance of good ventilation to mitigate spread via this route. The use of CO_2 monitoring as a surrogate measure of room ventilation is also advocated.

- **'Potential application of air cleaning devices and personal decontamination to manage transmission of COVID-19'** (Published on 4th November 2020) (SAGE-EMG 2020a): This report highlighted the potential role of supplementary air cleaning devices in poorly ventilated spaces. The report recommended the use of HEPA filtered and UVC devices, but did not advocate the use of other technologies such as ionisers.

- **'Application of physical distancing and fabric face coverings in mitigating the B117 variant SARS-CoV-2 virus in public, workplace and community'** (Published on 13th January 2021) (SAGE-EMG 2021): This report accepts that far-field (>2 metres) aerosol transmission of SARS-CoV-2 can occur, and using a classification system proposed by Milton (Milton 2020), suggests that exhaled respiratory particles should be reclassified as:

  (i) Respirable aerosols: particles <5 µm, which remain airborne for long periods and can penetrate to the deep lung on inhalation.

  (ii) Thoracic aerosols: particles 5-15 µm, which often remain airborne for more than 2 metres and can penetrate the thorax on inhalation.

(iii) Nasopharyngeal aerosols: particles 15-100 µm, that will normally only remain airborne for 1-2 metres unless air velocities are high, and will deposit in the nasal cavities and mouth following inhalation, or can deposit on mucous membranes.

(iv) Droplets: particles >100 µm, that behave ballistically, normally depositing within 2 metres and can cause infection by direct deposition onto mucous membranes.

142. From this we can see that the SAGE EMG reports broadly reflect the *'Covid-19 is not airborne'* to *'Covid-19 is airborne'* change that occurred in the scientific narrative outlined in Table 2. As new scientific evidence emerged, SAGE EMG revised its opinions, and updated its advice so that the UK Government, PHE/UKHSA and the public were aware of the latest developments in the field. As such, this was extremely helpful to all those: (i) formulating public health policy; (ii) formulating IPC policy within the NHS; and (iii) researching the transmission of SARS-CoV-2.

143. Notwithstanding the discussion above, it should be noted that some clinicians and academics have challenged the conclusion that SARS-CoV-2 can be transmitted by the airborne route. In particular, Carl Heneghan and co-workers (Heneghan et al. 2022) in a systematic F1000 review that was rejected by two out of four reviewers, came to the following conclusion: ***"SARS-CoV-2 RNA is detectable intermittently in the air in various settings ... (However,) The lack of recoverable viral culture of SARS-CoV-2 from air samples prevents firm conclusions about the definitive role of airborne transmission in SARS-CoV-2."*** This sentiment was echoed by Axon et al. (Axon et al. 2023), who suggested that the epidemiological work undertaken on the Skagit choir outbreak (Hamner et al. 2020; Miller et al. 2021) was flawed and questioned the conclusion that airborne transmission had arisen due to singing. However, the opinions set out in these two papers appear to be represent a minority position in the light of the 2024 WHO report (WHO 2024a), with a large body of evidence now supporting the position that Covid-19 is primarily spread via the aerosol route. Indeed, a work by Jaumdally et al. (Jaumdally et al. 2024) and others (Alsved et al. 2023b; Lednicky et al. 2020), who successfully cultured live virus from respiratory aerosol particles exhaled by Covid-19 patients, undermines the objections raised in Heneghan et al. (Heneghan et al. 2022).

144. The shift in the scientific consensus described above has only been reflected in the NIPCM guidelines to a limited extent, which currently (August 2024) list SARS-CoV-2 in Appendix 11a (https://www.england.nhs.uk/wp-content/uploads/2022/09/nipcm-appendix-11a-v2.7.pdf) as being transmitted by the *"droplet/aerosol"* route (NHS-England 2022). However, the status of aerosol transmission in this definition is ambiguous, and it is not clear whether this refers to respiratory aerosols naturally exhaled by Covid-19 patients, or to aerosols produced during AGPs, or both. Although it obliquely mentions both types, it is noticeable that HCWs are only required to wear FFP3 respirators when performing AGPs. By comparison, surgical masks are considered adequate for routine care of Covid-19 patients, despite the fact that much greater quantities of infectious aerosol are potentially produced when patients breathe, talk and cough (see paragraphs 154 to 158). This implies that the focus of the IPC guidance is more on the risks posed by AGPs than on the infectious aerosols exhaled by Covid-19 patients during their stay in hospital. As such, the UK IPC guidance appears not to reflect the scientific evidence that has emerged in recent years (and which has been embraced by the WHO) regarding the threat posed by exhaled infectious aerosols indoors.

145. The reasons for this ambiguity are unclear. It may be because many medical and IPC professionals still believe that ballistic respiratory droplets are the principal route by which SARS-CoV-2 transmission occurs, and have difficulty accepting evidence presented by physical scientists (as outlined above), preferring instead to rely solely on epidemiological evidence, or alternatively, relying on past routine practice as the default in the absence of epidemiological evidence. Conversely, it may also be because of confusion about the nature and behaviour of droplets and aerosols. For example, on their website explaining how Covid-19 is transmitted the

CDC state (August 2024): ***"COVID-19 spreads when an infected person breathes out droplets and very small particles that contain the virus. Other people can breathe in these droplets and particles, or these droplets and particles can land on others' eyes, nose, or mouth. In some circumstances, these droplets may contaminate the surfaces they touch"*** (CDC 2024a). Here, no mention is made of aerosols or the short-range ballistic behaviour of droplets, rather the terminology used is *"droplets and very small particles"*, which is extremely ambiguous. Indeed, on superficial inspection, it might appear that the CDC are advocating the traditional view of droplet transmission, which involves droplets impacting on the mucosa of eyes, nose and mouth. However, on closer inspection, it is quite clear that first and foremost the CDC is stating that Covid-19 spreads by the inhalation of infectious *"droplets and particles"* (i.e., airborne particles having a wide range of sizes), which implies the inhalation of infectious aerosols, exactly as described in Figure 1. After this, so-called 'droplet transmission is mentioned, although the term is not used. Therefore, it could be argued that the CDC is implying that inhalation of respiratory aerosols is the dominant route of SARS-CoV-2 transmission, although others dispute this (Cascella et al. 2023).

146. While the CDC statement on Covid-19 transmission acknowledges that both aerosol and droplet transmission can occur, it is noticeable that they highlight infectious particles exhaled by people with Covid-19 as the primary source. Therefore, in the context of hospitals, the CDC statement is entirely consistent with the view that the vast majority of infectious aerosols generated on wards are produced by exhalation (breathing, talking and coughing) and not by AGPs. **As such, the hierarchy in the NIPCM guidance, which places the threat posed by aerosols produced by AGPs (requiring FFP3 respirators) above aerosols exhaled by Covid-19 patients, appears misplaced** (see paragraphs 154 to 158).

Far-reaching IPC implications of incorrect historical thinking

147. The new scientific evidence revealed during the Covid-19 pandemic, together with a concomitant shift in thinking regarding the transmission of respiratory infections, has far-reaching implications for IPC and hospital ventilation guidelines in the NHS. Guidelines naturally tend to lag behind scientific advances, and so are often slow to change. Consequently, many of the current guidelines (in the UK and around the world) still reflect the historical assumption that respiratory viral infections are primarily transmitted via the "droplet route" and by various contact routes (CDC 2024c; NHS-England 2021a; NHS-England 2021b; WHO 2020). While there is still an ongoing scientific debate regarding the relative contribution of each mode of transmission, the overwhelming body of evidence indicates that the old historical model is likely to be incorrect, and that aerosol transmission is more important than previously thought. This has far-reaching implications for IPC transmission-based precautions (TBPs). In the following section a brief overview of these is given in the light of the shift in scientific thinking that occurred during the Covid-19 pandemic.

148. Although incorrect, the historical assertion that particles >5µm diameter (so-called 'droplets') could not travel further than about 1.5 metres became an accepted medical 'fact', and had far-reaching IPC implications. For example, individuals more than about 1.5 metres away from an infectious person were considered to be safe from inhaling respiratory particles >5µm, when in reality they were not. As such, maintaining a social distance of 2 metres, although helpful in reducing transmission, could not in itself prevent the far-field spread of SARS-CoV-2 indoors. This means that the current droplet verses airborne distinction used, for example, in the current Health Technical Memorandum (HTM) documents (NHS-England 2021a; NHS-England 2021b) on the ventilation of healthcare facilities is nonsensical and not fit for purpose (see Part 4 for details). Indeed, it is noticeable that the current (August 2024) NHS Scotland IPC guidelines, explicitly

refer to: ***"… droplets (greater than 5µm) …"***, and state that these cannot travel more than 1 metre (NHS-Scotland 2024a). Having said this, it is also noted that this statement contradicts the literature review undertaken for NHS Scotland in 2020 (Palma et al. 2020), which clearly recognises that exhaled respiratory droplets quickly evaporate to form small aerosols with a range of sizes (some >5µm and some <5µm), which can float in air. Indeed, the authors of this review go as far to state that ***"Droplets of less than 20µm can remain suspended in the air for many minutes"***, which concurs with the data showing in Table 1. So, in summary, it is likely that many statements still linger in the current IPC guidelines, which are, as of August 2024, still at variance with current scientific thinking on the transmission of respiratory viral infections.

149. Furthermore, it was wrongly assumed that virus was evenly distributed throughout the entire volume of exhaled respiratory particles. This meant that it was assumed that the vast majority (i.e., about 99%) of viruses were likely to be found in larger particles >10µm diameter (Nicas et al. 2005; PIP-Team 2011b; Weber & Stilianakis 2008), which according to the historical 'doctrine' could not travel further than 1.5 metres. However, this was incorrect, as numerous studies involving SARS-CoV-2 (Alsved et al. 2023a; Coleman et al. 2022; Jaumdally et al. 2024; Tan et al. 2023) and influenza (Bischoff et al. 2013; Coleman & Sigler 2020; Lindsley et al. 2010b; Yan et al. 2018) patients have shown, because that the majority of exhaled virus RNA actually found in the smallest aerosols which are <5µm diameter. The IPC implications of this are profound because it means that most of the viral load that is exhaled by infectious individuals is likely to be found in small aerosols that can travel many metres suspended in room air currents, rather than in large droplets (>100µm), which quickly fall to the floor. Current IPC guidelines in the UK and around the world do not reflect this, putting much more emphasis on the droplet route of transmission rather than on aerosols (CDC 2021; CDC 2024c; WHO 2020). When aerosol transmission is mentioned, it is usually in the context of so-called AGPs (see paragraphs 154 to 157 for details), and generally considered to be only a short-range transmission threat (NHS-England 2021a; NHS-England 2022), with respiratory aerosols generated by patients, visitors and HCWs generally given much less priority.

150. Another major implication of the shift in thinking concerns vocalisation, which was previously completely overlooked, but in the light of Covid-19 is now an issue of some importance. This is because individuals produce many more small aerosol particles when they talk compared with breathing, especially if they talk loudly (Alsved et al. 2020), with the result that much more virus can be exhaled into the air (Alsved et al. 2023a), without it being recognised as a problem. Previously, attention was mainly focused on the large droplets produced during coughing or sneezing, which meant that all the focus was on symptomatic transmission. By comparison, asymptomatic transmission received much less attention. However, asymptomatic individuals can still exhale many thousands of fine aerosol particles when breathing and talking, and failure to recognise this fact helps to explain why the contribution of asymptomatic transmission of SARS-CoV-2 was so greatly underestimated early in the Covid-19 pandemic. Although asymptomatic transmission is now recognised to be a problem in the NHS (Cooper et al. 2023), many of the IPC and ventilation guidelines do not reflect this, and focus instead on disease transmission in clinical spaces from patients who are symptomatic. By comparison, very little is mentioned about transmission in non-clinical spaces.

151. By classifying diseases as "droplet-borne" (as COVID-19 was initially classified, and influenza largely still is), the IPC community is essentially saying that the key issue is short-range droplet transmission (supplemented by hand-contact), and not the inhalation of aerosols, which are assumed to make minimal contribution. Accordingly, recommended IPC measures reflected this, with emphasis placed on: improved hand hygiene; surface disinfection; social distancing; and the

wearing of surgical masks. With regard to face masks, the emphasis is generally on preventing the ingress and egress of large droplets (i.e., protect against splashes and spray), not aerosols. So, during the Covid-19 pandemic, loose fitting surgical masks were considered adequate protection for this purpose, because they trap any large droplets that might be exhaled and prevent these from escaping. **They also protect the wearer from large ballistic droplets, exhaled by others, from impacting on the nose and mouth. However, as illustrated in Figure 1, a HCW in close vicinity to a Covid-19 patient is also potentially at risk from inhaling infectious aerosol particles of a range of sizes. The fact that surgical masks are ill-fitting, with gaps around face that allow the passage of aerosols, was not considered to be an issue, because according to the historical IPC consensus, aerosol transmission was generally thought not to be a major problem.** Therefore, by classifying Covid-19 and influenza as droplet-borne diseases, it effectively endorsed the use of surgical masks by healthcare staff, patients and visitors, rather than the wearing of close-fitting respirator masks (i.e., FFP 2 and 3 masks), which prevent the ingress and egress of aerosol particles aerosols (see Part 3 for details).

152. The classification of influenza and Covid-19 as "droplet-borne" diseases also impacts on the ventilation required in healthcare facilities. While room ventilation systems can be very effective at removing airborne particles up to about 20μm diameter, they cannot remove large droplets >100μm, because these rapidly fall to the floor. Therefore, if a disease is classified as "droplet-borne", by inference, the room ventilation rate will have no effect on its transmission. Therefore special air handing and ventilation systems are deemed not to be necessary (WHO 2014). However, if a disease is classified as being airborne and spread via aerosols, then these can be flushed away by ventilation air, with the result that providing adequate room ventilation becomes an important issue. So, the classification of the disease transmission route actually dictates the specification of ventilation systems in healthcare facilities (see Part 4 for details). Misclassification of the route of transmission can have profound implications on whether or not the ventilation rates specified in hospitals are appropriate for infection control purposes.

153. So, in summary, the paradigm shift that occurred in the scientific consensus during the Covid-19 pandemic was hugely important, because it challenges many previously held IPC assumptions regarding the transmission of respiratory viral infections. As such, it has highlighted a number of major inconsistencies between the current guidelines and state-of-the-art scientific thinking, which will have to be resolved.

Aerosol Generating Procedures (AGPs)

154. Although the vast majority of respiratory aerosols produced in hospitals buildings originate from patients, HCWs and visitors due to breathing, talking, coughing and sneezing, certain medical procedures, so-called **'aerosol generating procedures' (AGPs),** also release aerosols from the respiratory tract. As such, AGPs represent a potentially serious threat to clinicians performing procedures on patients who are infected, and so over the years they have received much attention (Bak et al. 2021; Hamilton et al. 2021; Jackson et al. 2020; NHS-England 2022; NHS 2022; PIP-Team 2011b; Tran et al. 2012), and are specifically covered in the *NIPCM for England* (NHS-England 2022), as well as in the 2021 HTM guidelines on the ventilation of hospital buildings (NHS-England 2021a).

155. AGPs are defined as procedures with a high risk of aerosol generation and increased risk of transmission from patients with a known or suspected respiratory infection. Medical procedures that are considered to be aerosol generating and associated with an increased SARS-CoV-2 transmission risk include: continuous positive airway pressure ventilation (CPAP); bronchoscopy;

respiratory tract suctioning; and tracheostomy procedures, although this list has been changed over time. The risks posed to HCWs undertaking these procedures have been assessed in a number of systematic reviews. For example, in 2012 Tran et al. (Tran et al. 2012) found that certain AGPs (notably tracheal intubation) in SARS patients was associated with increased risk to HCWs. However, in July 2021, Wilson et al. (Wilson et al. 2021) found an absence of evidence to support the view that procedures that induce coughing or involve respiratory suctioning were associated with an increased risk of SARS-CoV-2 transmission. Indeed, a rapid review undertaken for the NHS in June 2022 (NHS 2022) obtained mixed results, but did identify that some procedures, especially those performed on anaesthetised patients, posed little risk.

156. On 6th October 2020, Brown et al. (Brown et al. 2021) published a study which showed that coughing produced 35 times more aerosol particles than extubation, which in turn produced 15 times more aerosols than intubation. This caused the authors of the study to conclude that these procedures should not be designated as AGPs. Similarly, on 4th November 2021 the AERATOR Group published the results of a study which evaluated aerosol emissions associated with continuous positive airway pressure (CPAP) and high-flow nasal oxygen (HFNO) systems (Hamilton et al. 2022). These technologies are widely used to provide enhanced oxygen delivery and respiratory support for patients with severe COVID-19, and were both classified as AGPs. They found that CPAP produced less aerosol particles than breathing, speaking and coughing, with coughing associated with the highest aerosol emissions of any recorded activity. Likewise, aerosol emissions from the respiratory tract did not appear to be increased by HFNO.

157. These findings not only challenge historical assumptions about the amount of aerosol generated by AGPs, but are also important in the context of IPC guidelines, because the perceived risks associated with AGPs have driven much of the guidance concerning the use of respirator facemasks in the NHS (NHS-England 2022) (see Part 3 for details). However, it is noticeable that in the context of nosocomial transmission of SARS-CoV-2 and influenza, AGPs have received much more attention in comparison to respiratory aerosols exhaled by patients, HCWs and visitors during normal activities (i.e., breathing, speaking, etc.). **This is despite the fact that over the hours that an infectious person is present in a room, these everyday innocuous activities actually liberate many, many more respiratory aerosols into the air compared with AGPs, which may only last minutes.**

158. Although infectious aerosols produced by some AGPs pose a threat to HCWs, it would appear from the evidence presented above that for many AGPs the perceived risks have historically been over-exaggerated in comparison to those associated with breathing, speaking and coughing. The clinical aspects of this AGP designation are addressed further in the expert report from Professor Gould, Dr Warne, and Dr Shin.

Influenza and the 2011 Pandemic Influenza Preparedness (PIP) Report

159. In this section we focus on the transmission of influenza, and consider how historical thinking on this subject shaped pandemic preparedness in the UK. In particular, we consider in detail one of the PIP Team's reports, *Routes of Transmission of the Influenza Virus*, which in 2011 reviewed the scientific evidence on the routes by which influenza is transmitted (PIP-Team 2011b). It was subsequently published as (Killingley & Nguyen-Van-Tam 2013), and is noticeable because it took a holistic approach to the transmission of influenza, considering evidence from several

disciplines, but not engineering. This report was highly influential going into the Covid-19 pandemic, and shaped PHE/UKHSA policy on influenza (UKHSA 2013). It also helped to inform the 2021 HTM guidelines on hospital ventilation (NHS-England 2021a; NHS-England 2021b), as well as policy regarding PPE use when performing AGPs. This PIP report is also important because it was one of the first reports in the UK to highlight (albeit with major caveats) the potential for aerosol transmission of influenza over short distances (i.e., near-field transmission), while casting doubt on long-range (far-field) transmission; although, on this latter point, the PIP report is somewhat ambiguous.

160. Influenza has historically been considered to be primarily a "droplet-borne" disease, rather than airborne (HPIH&SD_PIP 2009). Indeed, in the table in Appendix 11a of the NIPCM (NHS-England 2022), influenza continues to be listed as a disease transmitted by droplets only. However, this position softened in the 2000's as it was realised that AGPs performed on influenza patients could generate infectious aerosols (HPIH&SD_PIP 2009; PIP-Team 2011b; WHO 2014), putting clinicians at risk. The PIP report addressed this issue, and while little epidemiological evidence existed to support the aerosol transmission of influenza in humans, the authors concluded that it was plausible that infectious aerosols might cause infection over short distances (i.e., <2 metres), but not over longer distances (PIP-Team 2011b). This has given influenza an ambiguous status and led to some confusion. It is not considered an airborne disease, but rather, droplet-borne, although the potential for short-range aerosol transmission of influenza has also been acknowledged (CDC 2021; PIP-Team 2011b). Indeed, the CDC currently (May 2024) state on their website that influenza is a droplet-borne disease that can also be transmitted by hand contact (CDC 2024c). So, although SARS-CoV-2 was reclassified as a "droplet/aerosol" infection in the NIPCM during the Covid-19 pandemic, the status of influenza has not changed (NHS-England 2022), despite the fact that the physical science underpinning transmission of both viruses is identical.

161. However, with a large body of evidence suggesting that SARS-CoV-2 can be transmitted via aerosols in both the near- and far-fields (Morawska et al. 2023; Prather et al. 2020a; Walport & RS Working Group 2023; WHO 2024a), the opinion that influenza is primarily droplet-borne has begun to be challenged. Indeed, well before the Covid-19 pandemic, evidence was mounting to suggest that aerosols might play an important role in the transmission of influenza (CDC 2021; PIP-Team 2011b). with some even suggesting that ***"the importance of droplet transmission has been overrated"*** (Weber & Stilianakis 2008). In addition, many scientific studies have shown that the virus can be transmitted in respiratory aerosols, pointing to airborne transmission of influenza (Bischoff et al. 2013; Coleman & Sigler 2020; Cowling et al. 2013; Kormuth et al. 2018; Lindsley et al. 2010a; Lindsley et al. 2010b; Moser et al. 1979; Yan et al. 2018). As such, influenza has a rather ambiguous status, which is leading to some confusion. Recently (May 2024), the WHO has attempted to clarify the situation, by included influenza amongst the list of pathogens transmitted through the air in its report: ***'Global technical consultation report on proposed terminology for pathogens that transmit through the air'*** (WHO 2024a). Although this report gives no adjudication as to whether influenza is primarily droplet-borne (newly referred to as "direct deposition") or airborne, its inclusion alongside notable airborne pathogens, such as measles and *Mycobacterium tuberculosis* (i.e., TB) suggests that the authors of the report think that airborne (aerosol) transmission also applies to influenza. Therefore, in the light of the Covid-19 pandemic, there is an ongoing debate regarding the extent to which the transmission of influenza might be airborne.

162. When the PIP Team undertook a comprehensive review of the transmission of influenza in 2011, it concluded that aerosols probably played a more important role in transmission of the disease

than previous thought (PIP-Team 2011b). However, they still considered droplets to be the principal route by which influenza is transmitted, but conceded that aerosol transmission might also play a role over short distances (i.e., <2 metres), or when AGPs are performed. The epidemiological evidence in support the aerosol transmission was considered inconclusive, as it was difficult to distinguish between droplet and aerosol transmission in the reported outbreak events. Consequently, the PIP Team concluded that long-range aerosol transmission was unlikely, stating: ***"Thus, the absence of evidence for long-range transmission does not preclude a significant role for short-range spread via aerosol-sized particles, in some circumstances, at ranges normally or traditionally attributed to only ballistic-sized larger droplets."*** (PIP-Team 2011b). The inference here being that respiratory aerosols are unlikely to infect people who are more than 2 metres away, which is inconsistent with the subsequent published work on aerosol evolution (Liu et al. 2017; Walker et al. 2020; Wei & Li 2015) and current understanding of how SARS-CoV-2 is spread (Alsved et al. 2023a; Alsved et al. 2023b; Beggs et al. 2024; Coleman et al. 2022; Jaumdally et al. 2024; Miller et al. 2021; Stadnytskyi et al. 2021; Stadnytskyi et al. 2020; Tang et al. 2021b; Wang et al. 2021a; WHO 2024a; Zhang et al. 2020).

163. Importantly, the PIP Team in their report did not use the 100µm droplet/aerosol threshold, now widely accepted for SARS-CoV-2 (Prather et al. 2020b; Tang et al. 2021a; Wang et al. 2021a). Rather they used the 10µm cut-off threshold proposed by Weber and Stilianakis (Weber & Stilianakis 2008), with large particles (>10µm) defined as droplets and small particles (≤10µm) as droplet nuclei (aerosols) (PIP-Team 2011b). The choice of this threshold was not based on aerosol physics, but rather on physiological grounds, because particles ≤10µm are respirable (i.e. capable of travelling deep into the lower respiratory tract), while particles in the range 10 – 100µm can only be inhaled into the upper respiratory tract (PIP-Team 2011b; Weber & Stilianakis 2008). Furthermore, they incorrectly assumed that all 'droplets' >10µm behaved ballistically, stating: ***"It (influenza) is mediated by large droplets (normally considered to be ≥10µm ...) which behave like ballistic particles ...)"*** This however is not the case, because aerosol particles as large as 20µm diameter take several minutes to fall out of the still air (Table 1), and therefore can transported far further than 2 metres, depending on the strength of room air convection currents (Obeid et al. 2023; Palma et al. 2020; Tang et al. 2021a).

164. Furthermore, the authors of the PIP report assumed that virus was evenly distributed throughout the entire volume of exhaled respiratory particles (based on assumptions in (Nicas et al. 2005)), and concluded that about 99% of the virus particles were likely to be found in particles >10µm diameter (PIP-Team 2011b). Consequently, they concluded that the infectious dose contained in the fine aerosols was likely to be very small and therefore unlikely to cause infection. However, numerous studies involving SARS-CoV-2 (Alsved et al. 2023a; Coleman et al. 2022; Jaumdally et al. 2024; Tan et al. 2023) and influenza (Bischoff et al. 2013; Coleman & Sigler 2020; Cowling et al. 2013; Kormuth et al. 2018; Lindsley et al. 2010b; Yan et al. 2018) patients have shown that the majority of exhaled viruses are found in the smallest aerosols which are <5µm diameter, rather than in the large droplets. As such, this undermines the key argument presented in the PIP report that the vast majority of the viral load is likely to be found in large droplets that do not travel far, rather than in smaller aerosols.

165. While the PIP report was written before most of the subsequent viral load distribution studies had been conducted, there were two studies in existence at the time by Lindsley et al. which showed that most of the virus exhaled by influenza patients was in respiratory particles <4µm (Lindsley et al. 2010a; Lindsley et al. 2010b). The authors of the PIP report were aware of Lindsley et al's findings (Lindsley et al. 2010b) and commented on them in their report. However, their

conclusions downplayed Lindsley et al's findings in favour of the assumption that most of the viral load is in the larger droplets.

166. While the authors of the PIP report (PIP-Team 2011b) acknowledged that aerosol particles <10µm could travel considerable distances, they concluded that the viral dose contained in these small aerosol particles was probably too low to initiate infection in most cases. However, this assumption appears incorrect on two counts: (i) as described above, the highest viral load is actually likely to be found in the smallest aerosol particles (Alsved et al. 2023a; Bischoff et al. 2013; Coleman & Sigler 2020; Coleman et al. 2022; Cowling et al. 2013; Jaumdally et al. 2024; Kormuth et al. 2018; Tan et al. 2023; Yan et al. 2018): and (ii) indoors, the respiratory aerosol concentration in the air will build-up over time. The analysis undertaken in the PIP report is rather simplistic and does not consider either the duration of exposure, or the build-up in aerosol concentration that occurs indoors over time, particularly in poorly ventilated spaces. Rather, the analysis appears to assume that as aerosols travel further away from an infector, so they become more and more diluted (i.e., ***"… the rapid diminution of concentrations of infectious aerosols as distance from the generating source increases"*** (PIP-Team 2011b), which although true outdoors, is not the case indoors (Beggs et al. 2024)*. From this the authors conclude that long-range (i.e., >2 metres) aerosol transmission of influenza was unlikely to occur because the inhaled virus dose would generally be far too low to cause an infection.

167. However, in reality, respiratory aerosol particles ≤10µm are more likely to contain virus particles, and can remain airborne in confined spaces for many minutes, depending on the size of the particle, with concentrations rapidly accumulating in poorly ventilated spaces (Beggs et al. 2024)*. Consequently, far from the viral load becoming diluted at distance from the source, indoors, the viral concentration in the room air will actually tend to increase as time progresses until a steady state threshold is reached. So, anyone spending several hours in a poorly ventilated space with an infectious person might be at considerable risk through far-field transmission, even if they are some distance away from the infector. This is because the cumulative dose inhaled will increase with time (Beggs et al. 2024)*, as occurred when 54 passengers spent 4.5 hours on board a commercial aircraft without mechanical ventilation, which resulted in a single passenger infecting 72% of the passengers with influenza (Moser et al. 1979).

168. Although some epidemiological evidence supporting far-field aerosol transmission (e.g., Moser et al. (Moser et al. 1979)) was presented in the PIP report, this was not considered strong enough, and so the report concluded: ***"...there is an absence of good quality epidemiological data to support long-range transmission of influenza via aerosols (suggesting that this phenomenon is rare or non-existent) ..."***. Yet in the report, three out of the eleven outbreak studies reviewed appear to implicate aerosol transmission over distances in excess of 2 metres, with an: ***"All routes possible"*** conclusion reached for a further six studies. This appears to challenge the conclusion of the report that ***"long-range transmission is rarely reported and is unlikely to be important"*** (PIP-Team 2011b).

169. In 2011 when the PIP report was written there was in existence a large body of work concerning the risks posed by droplet-nuclei and airborne pathogens in buildings, with the Wells-Riley epidemiological model having been used for many years to assess the far-field risk of acquiring infections such as TB and measles (Beggs et al. 2003; Nardell et al. 1991; Noakes et al. 2006a; Riley et al. 1978; Riley 2001)*. As such, it was well recognised that in occupied room spaces, the concentration of droplet-nuclei (i.e., aerosols <10µm) tends to increase over time until an equilibrium level is reached, which will depend on the ventilation rate. Yet, the PIP report ignored this body of evidence, instead assuming that the exhaled aerosol concentration becomes

progressively diluted with distance from the source, leading to the conclusion that the influenza viral load tended towards zero in the far-field. However, while this happens outdoors, it is not what happens indoors, especially in poorly ventilated room spaces (Beggs et al. 2024)*.

170. While the scientific literature relating to airborne transmission of infection indoors was largely ignored, it is nonetheless noticeable that the PIP report (PIP-Team 2011b) alludes to the phenomenon described above, stating: ***"... it should be appreciated that the risk of infection may vary. For example a super-spreading patient who emits a large bioaerosol load into a contained indoor environment during winter time may represent a much higher aerosol infectious risk than that posed by a patient emitting a low bioaerosol load occupying a well ventilated room during summer."*** However, while acknowledging that the concentration of aerosols can increase indoors under certain circumstances, the report is very ambiguous about this, and fails to consider in any quantitative way the implications of the build-up of infectious aerosols that occurs in buildings over time, particularly when they are poorly ventilated.

171. Evidence supporting the view that small aerosols can transmit influenza comes from numerous studies in which influenza (RNA and viable virus) has been recovered from droplet nuclei <5µm, either directly from influenza patients (Bischoff et al. 2013; Lindsley et al. 2010b; Yan et al. 2018), or from the air in healthcare facilities (Lindsley et al. 2010a) and other settings (Coleman & Sigler 2020; Lednicky & Loeb 2013; Yang et al. 2011). Given that influenza can survive in aerosols for several hours (Weber & Stilianakis 2008), this suggests that the accumulation of aerosols containing the virus may contribute to far-field transmission of influenza indoors.

172. Although somewhat ambiguous about the aerosol transmission of influenza, the PIP report (PIP-Team 2011b) nevertheless came to some conclusions which were highly relevant to the deployment of facemasks during the subsequent COVID-19 pandemic. In particular, the reports concluded that the ***"... role for aerosol transmission from some infected individuals in the absence of known aerosol generating procedures cannot be ruled out ..."***, cautiously conceding (for the first time) that the near-field aerosol spread of influenza is likely a real phenomenon in the absence of AGPs.

173. With specific reference to AGPs, the report then went on to concluded: ***"In healthcare settings the use of high-level respiratory protection (FFP3* respirators) for known aerosol generating procedures performed on patients infected with influenza remains appropriate."*** Although, it is noticeable that the report then stated: ***"* Scientifically FFP2 standard (US equiv N95) respirators are likely to be adequate for the prevention of aerosol transmission of influenza but the UK regulatory framework set by HSE [the Health and Safety Executive] only permits the use of FFP3 standard equipment."***

174. Importantly, the report then goes on to say: ***"In the absence of performing procedures that are known specifically to be aerosol generating (e.g. during routine close-range patient care), aerosol transmission might still occur; in these circumstances surgical face masks would not be fully protective."*** This statement is highly pertinent to IPC practice during the Covid-19 pandemic, during which, the wearing of surgical face masks was the principal personal protective equipment (PPE) measure recommended for HCWs when not performing AGPs.

175. When considered as a whole, the PIP report makes the important contribution of flagging up possible aerosol transmission of influenza at short-range (<2 metres), something that would have been helpful in formulating policy during the COVID-19 pandemic. However, the report is much more ambiguous regarding the long-range (far-field) aerosol transmission of influenza, due in part, to a failure to consider exposure time, and the large body of evidence relating to calculating

the risk of acquiring an airborne infection in buildings (i.e., the Wells-Riley model, etc.). **The reason for this may in part be due the *a priori* assumption that influenza is a droplet-borne disease, rather than airborne disease.** The lack of any engineering input into the report, might also have contributed to some of the misconceptions in the report concerning the nature and behaviour of aerosols. Also, in 2011 when the PIP report was produced, the evidence base was not as complete as it is now (August 2024).

176. Subsequent knowledge acquired after 2011 and during the Covid-19 pandemic now challenges many of the conclusions in the PIP Team report regarding the aerosol transmission of infectious disease (PIP-Team 2011b). Notwithstanding this, the report was used to formulate IPC policy during the pandemic. For example, closely mirroring the conclusions of the PIP report, in July 2020 the SAGE Environment and Modelling Group stated in their ***"Role of Aerosol Transmission in COVID-19"*** report (SAGE-EMG 2020b): ***"Aerosol transmission can occur when small respiratory aerosols (<10µm diameter) containing the virus remain in the air and can be inhaled by another person. This is most likely to happen at close range (within 2m) though there is a small amount of evidence that this could happen in an indoor environment more than 2m from an infected person. There is currently no evidence for long range aerosol transmission where the virus is dispersed between rooms in a building or long distances outdoors."*** The PIP report also likely informed preparation of the 2021 Health Technical Memorandums (HTMs) (03-10 Parts A and B) on the ventilation of hospital buildings (NHS-England 2021a; NHS-England 2021b).

Part 3: Face masks, respirators and visors

Key findings:

- All facemasks inhibit the exhalation and inhalation respiratory particles to a greater or lesser extent.
- Surgical masks are loose-fitting and, if worn correctly, are effective against large droplets which might otherwise land on the nose and mouth of the wearer. Their effectiveness against inhaling smaller particles is low, but better than nothing.
- Surgical masks are primarily designed as source control, that is, to trap exhaled large droplets. They are less effective at trapping smaller exhaled particles, which can escape through the gaps between the mask and the face.
- Respirators are tight-fitting and effective against a wide range of infectious respiratory particle sizes. They are designed for higher-risk situations to ensure protection for the person wearing the respirator. In UK healthcare settings, the type of respirator used is primarily FFP3. Some respirators have exhalation valves that mean that they cannot be used for source control.
- Visors only protect against splash from the largest droplets and offer no protection against inhalation, although they do protect against any potential risk of transmission via the eyes, as do goggles.
- Fit testing is used to ensure no leakage when respirators are used. If someone's facial anatomy does not fit to any of the available masks, a powered hood can be used instead of a respirator that fits tightly to the face.
- Respirators are more challenging to use than surgical masks. Different models will not fit everyone. Where they use tight straps around the head, they are more effective but also more uncomfortable.
- Most facemasks are designed to be disposed of regularly to ensure effectiveness and to prevent the mask from becoming a fomite. Reusable respirators can reduce waste production, but safety issues associated with the valves integral to their design means that their use is generally limited only to certain non-sterile applications.
- Masks are complex non-pharmaceutical interventions, and proving their real-world effectiveness is challenging due to numerous confounding factors and biases (especially user behaviour), variable study conditions, and conflicting findings.
- Randomised controlled trials (RCTs) are traditionally emphasised as the highest standard of evidence, but their use in assessing drugs cannot simply be replicated for masks.
- The most comprehensive evidence reviews consider a wider variety of types of scientific evidence, and have found that respirators are more effective for reducing transmission than surgical masks, which are more effective than no mask at all.

177. In Part 3, the physical science underpinning the use of facemasks, respirators, visors (shields) and goggles in healthcare facilities is explained, and the limitations of each technology discussed.

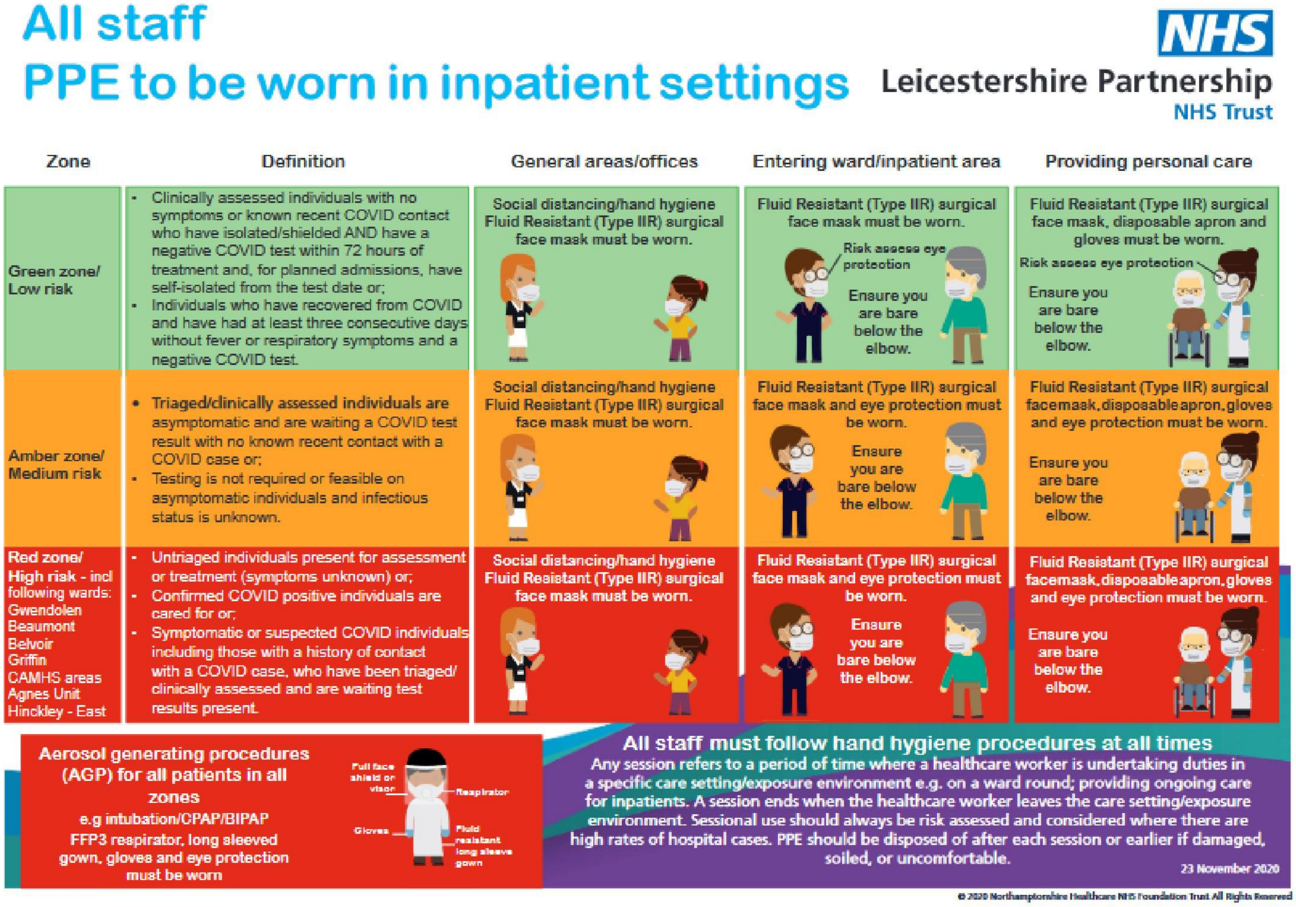
As such, Part 3 is primarily concerned with the physical science, and not clinical practice, or IPC guidelines, which are discussed in general terms only. In addition, the epidemiological evidence in support of face masks is evaluated.

178. Facemasks, respirators, visors are technologies designed to interrupt the transmission of pathogens through the air. However, while facemasks and respirators are intended to cover the nose and mouth, thus inhibiting (or preventing) the egress and ingress of a range of respiratory particle sizes, visors are designed to protect the eyes and face from infectious droplets that might otherwise impact on them. Goggles do a similar job to face visors, but do not protect the face, nose and mouth from droplets.

179. All facemasks inhibit the transport of larger respiratory droplets and aerosol particles to a greater or lesser extent. However, some are much more effective at doing this than others. In Part 3, we will consider the two main types of facemask used in NHS healthcare facilities, surgical masks and respirator masks (FFP3 being the standard respirator type in UK healthcare settings). Surgical masks are loose fitting masks that cover the nose and mouth, and are widely used in the NHS. They are primarily designed to protect the wearer against "splashes and spray", but are also good at interrupting the transport of large respiratory droplets, which when exhaled get trapped in the fabric of the mask, but are much less effective at interrupting the passage of aerosols compared with a respirator mask. Respirator masks by comparison, are tight (close) fitting, and use a high-quality fabric that filters out almost all particles from the air. As such, respirator masks are highly effective at preventing the passage of both large droplets and small respiratory aerosols.

180. Many people get confused about the purpose of facemasks, thinking that their primary function is to protect the wearer. However, while this is true for respirators, it is only partially true for surgical masks. This is because surgical masks are loose fitting and much better at trapping droplets and aerosols exhaled by the wearer than they are at preventing the inhalation of aerosol particles. Therefore, the primary purpose of surgical masks is to trap at source potentially infectious droplets and aerosols exhaled by the wearer to prevent these from infecting others (Kahler & Hain 2020). Having said this, surgical masks also afford the wearer limited protection against inhaling respiratory particles. By comparison, tight fitting respirator masks are very good at protecting the wearer from inhaling infectious aerosols, and thus are generally reserved for situations where the risk to the wearer is perceived to be elevated.

181. At one stage during the Covid-19 pandemic most NHS hospitals cohorted inpatients according to the colour scheme set out in Figure 12, which comprised three zones: green wards for Covid-negative patients, with no symptoms; amber wards for asymptomatic patients who are waiting for Covid test results; and red wards housing confirmed Covid-positive patients. Figure 12 shows the guidance that applied to inpatient areas in the Leicestershire Partnership NHS Trust in November 2020. From this, it can be seen that in this hospital trust at the time, surgical masks were required to be worn in all zones, with the use of respirator masks and visors reserved for AGPs performed in any zone. However, it should be noted that Figure 12 is for illustrative purposes only, as PPE guidance regularly changed throughout the pandemic. The evolution of these guidelines over time is covered in more detail by Dr Shin, Professor Gould and Dr Warne in their expert report on the clinical aspects of IPC.



All staff
PPE to be worn in inpatient settings

NHS
Leicestershire Partnership
NHS Trust

Zone	Definition	General areas/offices	Entering ward/inpatient area	Providing personal care
Green zone/ Low risk	- Clinically assessed individuals with no symptoms or known recent COVID contact who have isolated/shielded AND have a negative COVID test within 72 hours of treatment and, for planned admissions, have self-isolated from the test date or; - Individuals who have recovered from COVID and have had at least three consecutive days without fever or respiratory symptoms and a negative COVID test.	Social distancing/hand hygiene Fluid Resistant (Type IIR) surgical face mask must be worn.	Fluid Resistant (Type IIR) surgical face mask must be worn. Risk assess eye protection Ensure you are bare below the elbow.	Fluid Resistant (Type IIR) surgical face mask, disposable apron and gloves must be worn. Risk assess eye protection Ensure you are bare below the elbow.
Amber zone/ Medium risk	- Triaged/clinically assessed individuals are asymptomatic and are waiting a COVID test result with no known recent contact with a COVID case or; - Testing is not required or feasible on asymptomatic individuals and infectious status is unknown.	Social distancing/hand hygiene Fluid Resistant (Type IIR) surgical face mask must be worn.	Fluid Resistant (Type IIR) surgical face mask and eye protection must be worn. Ensure you are bare below the elbow.	Fluid Resistant (Type IIR) surgical facemask, disposable apron, gloves and eye protection must be worn. Ensure you are bare below the elbow.
Red zone/ High risk - incl following wards: Gwendolen Beaumont Belvoir Griffin CAMHS areas Agnes Unit Hinckley - East	- Untriaged individuals present for assessment or treatment (symptoms unknown) or; - Confirmed COVID positive individuals are cared for or; - Symptomatic or suspected COVID individuals including those with a history of contact with a COVID case, who have been triaged/ clinically assessed and are waiting test results present.	Social distancing/hand hygiene Fluid Resistant (Type IIR) surgical face mask must be worn.	Fluid Resistant (Type IIR) surgical face mask and eye protection must be worn. Ensure you are bare below the elbow.	Fluid Resistant (Type IIR) surgical facemask, disposable apron, gloves and eye protection must be worn. Ensure you are bare below the elbow.

Aerosol generating procedures (AGP) for all patients in all zones
e.g intubation/CPAP/BIPAP
FFP3 respirator, long sleeved gown, gloves and eye protection must be worn

All staff must follow hand hygiene procedures at all times

Any session refers to a period of time where a healthcare worker is undertaking duties in a specific care setting/exposure environment e.g. on a ward round; providing ongoing care for inpatients. A session ends when the healthcare worker leaves the care setting/exposure environment. Sessional use should always be risk assessed and considered where there are high rates of hospital cases. PPE should be disposed of after each session or earlier if damaged, soiled, or uncomfortable.

23 November 2020

Figure 12. Mask wearing guidance for healthcare workers during the Covid-19 pandemic (source: Leicestershire Partnership NHS Trust, November 2020)

Fluid-resistant (Type IIR) surgical masks (FRSM)

182. During the Covid-19 pandemic, HCWs were required to wear surgical masks on wards and when attending to patients (see Figure 12). In addition, inpatients with suspected or confirmed Covid-19 were also asked to wear surgical masks (NHS-England 2022). These facemasks were generally fluid-resistant (Type IIR) surgical masks (FRSM), with ear loops that meet the International Standard (EN14683), as shown in Figure 13. Such masks are disposable and

generally have a rectangular shape with pleats that allows the mask to better hug the contours of the face. They are generally constructed using three layers of material, are splash resistant, and have a bacterial filtering efficiency (BFE) >98% for particles 3μm diameter (Whyte et al. 2022).

183. Although FRSMs provide protection against large droplets impacting on the nostrils and mouth, they also perform the important role of trapping exhaled droplets at source so that they cannot infect others, or contaminate surfaces. Importantly, despite having a BFE rating >98%, FRSMs cannot prevent inhalation of fine aerosols. This is because they are loose fitting, with the result that aerosol particles suspended in the inhaled air can bypass the mask via the gaps at the side of the face (see Figure 13). Similarly, while some exhaled respiratory aerosols become trapped in the fabric of the mask, many other fine particles can escape through the gaps between the mask and the face (see Figure 14). **So, in short, FRSMs provide only minimal protection against the inhalation of infectious aerosols, because they are loose fitting, which is why the NIPCM states that should not be worn when undertaking AGPs (England 2022).**

184. Notwithstanding, the inability of FRSMs to completely prevent the inhalation of infectious aerosols, there is evidence that they do provide some protection to the wearer, with a RCT involving the wearing of surgical face masks in public places showing a reduced risk of self-reported symptoms consistent with respiratory infection (Solberg et al. 2024). Whether this protective effect was due to protection against large droplets impacting on the nose and mouth, or reduced aerosol inhalation is however not known.

Figure 13. Woman wearing surgical mask with ear loops. Kristoffer Trolle from Copenhagen, Denmark, CC BY 2.0 <https://creativecommons.org/licenses/by/2.0>, via Wikimedia Commons]

185. The effectiveness of surgical masks at inhibiting the passage of exhaled respiratory particles is illustrated in the Schlieren images in Figure 14 (reproduced from Bhagat et al. (Bhagat et al. 2020)), which shows that, despite being loose fitting, the mask can prevent the formation of an exhalation plume. Having said this, it can also be seen that leakage occurs around the mask, allowing smaller aerosols to escape through the gaps between the mask and the face. (NB.

Bhagat et al. (Bhagat et al. 2020) performed their Schlieren experiments using a non-surgical 3-ply mask (EN14683) which is identical to a surgical mask, but has a BFE rating of >95%.)

186. From Figure 14, it is noticeable that although wearing the masks prevents the formation of an exhalation plume, it redirects the exhaled aerosols upwards through the gap at the top of the mask so that they are entrained in the thermal plume that continually flows over the face and rises above the head (see Figures 7 and 8). Once entrained into the thermal plume the exhaled aerosol particles can be quickly dispersed around the room, as shown in Figure 8.

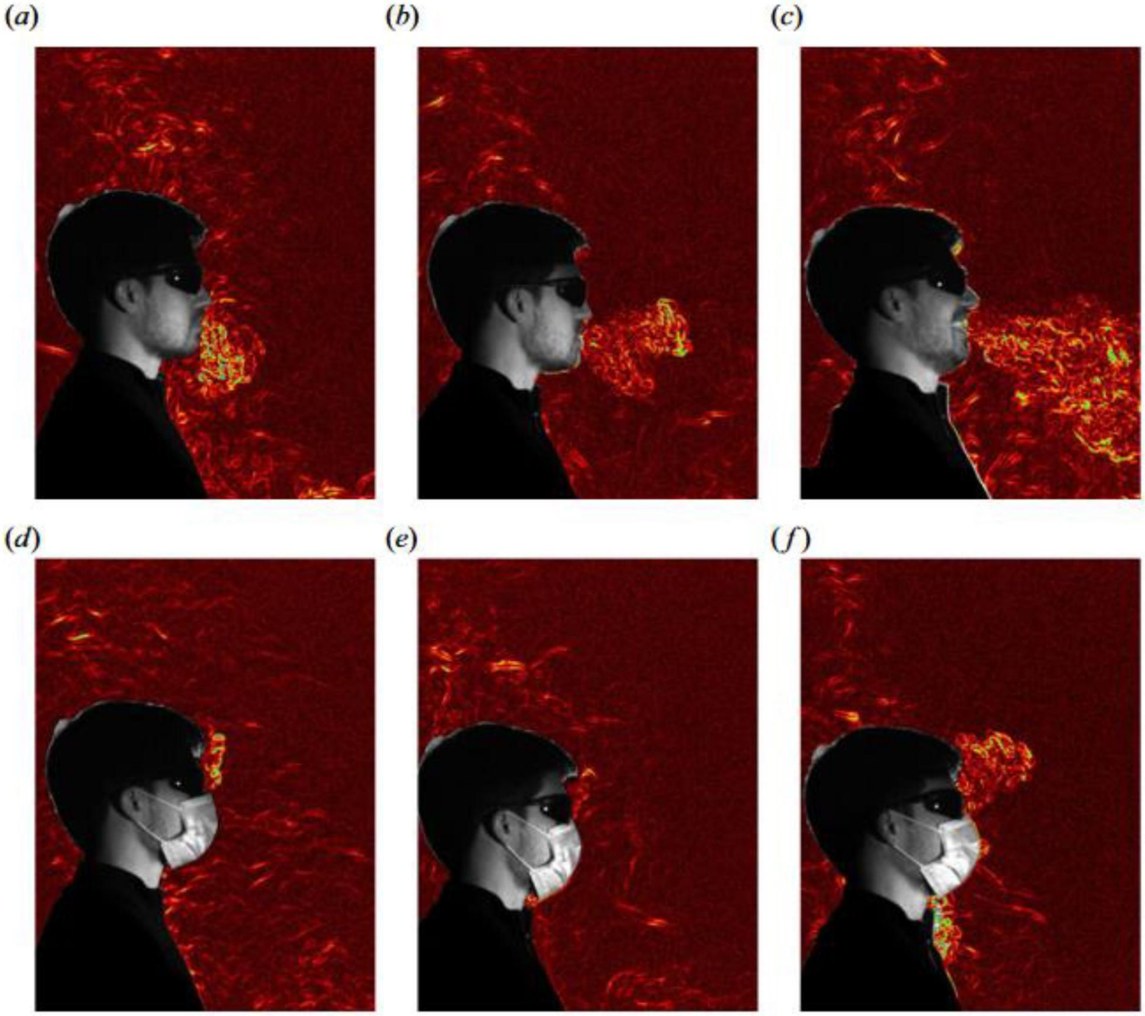


Figure 14. Schlieren images highlighting the thermal and exhalation plumes produced by a seated subject with and without a surgical mask. In panels (a-c) no mask is worn, while in panels (d-f) the subject wears a non-surgial mask. In: (a & d) the subject is sitting quitely breathing through their nose; (b & e) the seated subject is saying ‘also’, speaking at a conversational volume; and (c & f) the subject is laughing. (Images reproduced from Bhagat et al. [57] (CC BY 4.0) (Bhagat et al. 2020)).

Respirator (FFP2 and FFP3) masks

187. Respirator masks are tight fitting and effective against inhalable aerosols. In the UK these fall into two main classes: FFP2 (equivalent to N95 masks in the USA) and FFP3 masks (equivalent to N99 masks in the USA). Here, FFP stands for 'Filtering Face Piece'. FFP2 respirators have a filtration efficiency >94% for particles of size 0.3µm diameter, whereas FFP3 respirators have an efficiency of >99%. Both types of respirator mask are designed to protect the wearer against inhalation of infectious aerosols, and when fitted correctly are effective against SARS-CoV-2 (Wilson et al. 2020). To be fully effective, they must be close fitting with no gaps around the face. With this in mind, in the UK the use of FFP2 and FFP3 masks with ear loops is not recommended, as these do not ensure a tight enough fit (Knobloch et al. 2023) (see paragraphs 227 to 228 for further discussion of FFP masks with ear loops). Rather, behind-the-head straps are recommended by the NHS (see Figure 15), with fit tests required to ensure that respirator masks are correctly fitted. Additionally, the HSE mandate that FFP2 masks should not be used in the NHS unless stocks of FFP3 respirators are exhausted (INQ000347822: Witness statement of Richard Brunt, Director of Engagement and Policy Division, the Health and Safety Executive, paragraphs 268 and 269).

Figure 15. Typical FFP3 respirator mask with behind-the-head straps. (Source: Cambridge University Hospitals NHS Foundation Trust website: https://www.cuh.nhs.uk/news/drop-in-staff-covid-19-infections-after-ppe-upgrade/)

188. The outer layer of both types of respirator mask is typically made from a durable, non-absorbent material that provides structural support to the mask. The core of the mask consists of multiple filtering layers designed to capture very fine particles. This is of a higher standard for FFP3 masks and allows for a greater level of filtering compared with FFP2 respirators.

189. Some FFP2 and FFP3 masks have an exhalation valve to make breathing more comfortable for the wearer. However, the inclusion of this valve allows unfiltered air to be expelled into the room space, increasing the risk of transmitting infection to others. The use of respirator masks with exhalation valves is therefore not recommended in the NHS in England. However, as of August

2024, the Scottish NPICM merely states that "unshrouded" valved respirators are not fluid resistant, and so should be only be used with a face shield if fluid splash is anticipated (NHS-Scotland 2024b).

190. Because poorly fitted respirator masks can compromise the safety of HCWs, the NHS has procedures to ensure that they are correctly fitted (NHS-England 2024). During the Covid-19 pandemic a fit test programme was developed and rolled out across the NHS, details of which are beyond the scope of this report and are covered by Professor Gould, Dr Shin and Dr Warne in their report. However, from a physical science standpoint, the key issue involved in fit testing is to ensure that no leakage occurs to or from the mask, by which aerosols can bypass the filtering mechanism. Therefore, it is essential that during training HCWs are shown how to: (i) inspect the integrity of the mask; and (ii) ensure that mask is tightly fitted so that there are no gaps between it and the face.

Contamination, handling and disposal of surgical masks and respirators

191. The surgical and respirator masks used in the NHS are disposable, and are intended to be used for a limited period only, which varies depending on the type of mask. Both respirator and surgical mask can become damp over time, due to moisture in exhaled breath, and this can greatly increase resistance to inhalation, as well as causing a build-up of potentially harmful bacteria (Guan et al. 2022). It may also reduce the integrity of masks. Therefore, masks need to be discarded after a period of time and new ones fitted. Contaminated masks need to be handled and disposed of with care, so that infection is not transmitted by the contact route. In clinical spaces discarded masks should be treated as clinical waste and disposed of accordingly.

192. There is no set limit for the length of time that single-use surgical masks can be worn. However, it is generally accepted that during a working day, surgical masks will be replaced fairly regularly when they get wet (damp) or dirty, or when they are damaged. Furthermore, once taken off to eat or drink, they should be disposed of and a new one worn after eating or drinking. The scientific evidence suggests that although filter efficiency remains largely unchanged for up to 6 hours, after about 2 hours of wearing, surgical masks become damp, with the result that it becomes increasingly difficult to inhale (Guan et al. 2022). So, it is likely that users will naturally tend to replace such masks after about 2 hours of use. Details of how NHS guidance on this subject changed during the pandemic are beyond the scope of this report and are covered by Professor Gould, Dr Shin and Dr Warne.

193. Because they are tight fitting and have head straps, respirator masks (both FFP2 and FFP3) tend to be more uncomfortable compared with surgical masks, with skin temperature dramatically rising after about 2 hours (Guan et al. 2022). Like surgical masks, they too become damp and suffer from increased inhalation air resistance, and therefore it is recommended that respirator masks be replaced after about 2 hours of wear (Guan et al. 2022), or after specific AGPs have been performed.

194. The inner and outer surfaces of masks may become contaminated with virus or bacteria (Tcharkhtchi et al. 2021), making removal and disposal of the mask a potential hazard. Various studies have been undertaken to assess: the infection risk posed by contaminated masks (Fouda et al. 2021); changes in mask efficacy with time (Guan et al. 2022); and mask decontamination

techniques (Ludwig-Begall et al. 2021; Rodriguez-Martinez et al. 2020), but these have been rather ad hoc and much still remains unknown on this subject. (NB. The author has only very limited knowledge of mask disposal and decontamination techniques.)

195. As with all clinical activities where hands can become contaminated, appropriate hand hygiene measures (e.g., wearing disposable gloves, handwashing, using alcohol gel, etc.) should be taken when handling and disposing of used facemasks. With respect to this, washing with soap and water is highly effective, because the soap disrupts the envelope of the SARS-CoV-2 virus, rendering incapable of infection (Ijaz et al. 2021). However, when handwashing facilities are not available, hand sanitizers with an alcohol content >60% can also be effective.

Reusable respirators and powered hoods

196. In addition to disposable FFP3 respirators, there are a number of reusable alternatives, some of which are permitted for use in the NHS (NHS-England 2022). These include reusable respirator masks and powered respirator hoods, which both contain high efficiency filters that can be replaced. As with their disposable counterparts, these devices are only permissible if they do not have exhalation valves (NHS-England 2022). Rather confusingly however, reusable respirators are specifically mentioned in Chapter 2: 'Transmission based precautions (TBPs)' of the NIPCM for England (NHS-England 2022), which implies that they are permissible. However, this contradicts the requirement that masks with exhalation values should not be used. This is because most reusable respirator masks have a valve, which allows the exhaled breath and liquid condensation to escape, and there is the potential risk of infectious material dripping into a *sterile field* during, for example, surgery. This concern was highlighted and addressed in a ***National Patient Safety Alert* issued on the 25th August 2021** (NHS-England 2021d) (see paragraph 198 for details).

197. Loose fitting powered respirator hoods are an alternative to tight-fitting FFP3 masks, that are recommended ***"when fit testing cannot be achieved"*** (NHS-England 2022). They fit over the HCWs head and can be reused (after decontamination), although some types are disposable. They are distinguished from other respirators in so much that they have a fan, which draws room air through a HEPA filter pack (attached by a belt to the waist), which is then pushed up to the hood, before escaping around the shoulders. As with reusable respirators with valves, the air exiting such hoods is not filtered, leading to similar safety concerns that contaminated material might fall from the gap under the hood into a *sterile field* (NHS-England 2021d).

198. As mentioned above, safety concerns about dripping condensate were addressed in a ***National Patient Safety Alert* issued on the 25th August 2021** (NHS-England 2021d), which specifically stated that powered hoods and valved FFP3 respirators should not be used by HCWs undertaking sterile procedures or used directly over the surgical field. However, it does permit the use of these types of RPE for staff whose only option is a powered hood or valved respirator, provided that it is not used in the aforementioned context.

199. Notwithstanding this, it should be noted that because valved respirators and powered hoods allow unfiltered exhalation air to exit, there is a risk that an asymptomatic wearer of such equipment could discharge infectious aerosols into room air. However, the risks associated with this are essentially similar to those for HCWs who wear FRSMs.

Face visors and goggles

200. Face visors, such as the one illustrated in Figure 16, are recommended for use by HCWs when performing AGPs (see Figure 10), where there is a risk of infection being transmitted by the so-called "droplet route". These form a personal transparent barrier and protect against large respiratory droplets (>100μm) impacting on the eyes and face. Face visors are, however, ineffective against tiny airborne aerosol particles which simply travel around the transparent shield during inhalation. For this reason, when performing AGPs, FFP3 respirator masks which cover the nose and mouth are also currently (August 2024) recommended (NHS-England 2022) when face visors are used as shown in Figure 16.

201. As an alternative to face visors, reusable plastic goggles can be used when treating patients.

Figure 16. A healthcare worker wearing a face visor and respirator mask. [By Matt Hecht - https://www.flickr.com/photos/76858203@N04/49696558958/, Public Domain, https://commons.wikimedia.org/w/index.php?curid=89580959]

Compliance

202. Although rules on masks wearing evolved over the course of the Covid-19 pandemic (NHS-England 2021c), broadly speaking, everyone accessing or visiting healthcare settings were required to wear a face covering (usually surgical masks) and follow social distancing rules. This requirement applied to patients, visitors and all HCWs, with the general aim of reducing the risk of healthcare acquisition of SARS-CoV-2.

203. Although mask wearing compliance amongst HCWs on hospital wards was generally high, less is known about patients and visitors, and it is likely that compliance levels amongst these groups were much lower than that for HCWs (Rathod et al. 2021). Indeed, with respect to mask wearing, hospital inpatients posed a particular challenge, with ill and often confused patients sometimes asked to wear masks continuously - something that was difficult to enforce. Many patients could not tolerate wearing masks for long periods, especially when in bed, where masks could easily become dislodged. Furthermore, patients had to remove their masks when eating and drinking, or when taking medication, all of which added to general non-compliance.

204. A major surveillance study of 145 English NHS acute hospital trusts (Cooper et al. 2023) concluded that, for the period June 2020 to March 2021, ***"patients who themselves acquired SARS-CoV-2 infection in hospital were the main drivers of transmission to patients, whereas transmission from both HCWs and nosocomially infected patients were of similar importance for transmission to HCWs."*** In other words, patients who became infected in hospital were significant drivers of infection amongst both HCWs and other patients. This important finding confirms earlier work by Illingworth et al. (Illingworth et al. 2021) undertaken at a Cambridge teaching hospital during the first wave of the pandemic from March to June 2020. They found that patients were much more likely to acquire a SARS-CoV-2 infection from other patients than from HCWs. They also observed a consistent pattern of superspreading, with 21% of individuals causing 80% of transmission events. Having said this, it should be remembered that the Covid-19 pandemic was mainly driven by SARS-CoV-2 transmission in the community, therefore HCWs and visitors could introduce the virus into hospitals from the community.

205. Given this, mask wearing compliance amongst patients must be considered an issue of great importance, especially since much Covid-19 transmission involves people who are asymptomatic or pre-symptomatic (Gandhi et al. 2020; Hu et al. 2020). Yet, in comparison to the attention given to HCWs, the important issue of compliance amongst patients has received much less attention, which is somewhat surprising, given that many patients are immunocompromised and therefore vulnerable to infection.

206. This issue was highlighted by Illingworth et al. who noted early in the pandemic, that although: ***"face mask usage was enforced for individuals in outpatients and for HCWs in all areas of the hospital, inpatients were not at the time of data collection subject to the same precautions."*** (Illingworth et al. 2021). From this it was concluded that mask wearing amongst inpatients was essential in order to reduce patient-to-patient and patient-to-HCW transmission, especially when the infectious patients were asymptomatic. They recommended that all patients, including those on non-COVID wards, should wear surgical masks - a recommendation subsequently adopted by the NHS, although, as discussed above, mask wearing by inpatients proved difficult to enforce.

207. Illingworth et al. (Illingworth et al. 2021) and Cooper et al. (Cooper et al. 2023) both found that HCW-to-HCW cross-infection was also a feature of SARS-CoV-2 transmission in hospitals. Anecdotal evidence suggests that mask wearing compliance was less amongst HCWs who were in non-clinical areas, such as staff-rooms and dining areas during the pandemic (Dancer 2021). As such, this likely contributed to nosocomial transmission of SARS-CoV-2 amongst HCWs. Staff-rooms in particular, were a major infection risk, because these spaces are often very poorly ventilated and HCWs take their masks off to eat and drink.

208. Poor compliance regarding the wearing surgical masks is often cited as a contributing factor to the nosocomial transmission of SARS-CoV-2 in UK hospitals (Brooks et al. 2021). However, whilst a likely contributor, it is important to point out that even with perfect compliance, surgical masks are not designed to prevent inhalation of infectious aerosols (see, e.g., paragraph 183), so the risk of airborne transmission still remains. This point was reinforced in the SAGE report, *"Masks for healthcare workers to mitigate airborne transmission of SARS-CoV-2"* (published 9th April 2021), which placed good ventilation above the wearing of surgical masks in the hierarchy of controls (SAGE-HOCI 2021). By doing so, SAGE were acknowledging the importance of reducing the viral load in room air in order to reduce the risk of inhaling infectious aerosols when wearing surgical masks.

Evidence concerning the effectiveness of mask types

209. Given that HCWs spend long periods of time in crowded ward spaces that that may be poorly ventilated, during the pandemic they were potentially at risk of acquiring SARS-CoV-2 whether or not they were in close proximity to infectious patients or other HCWs. Evidence from Cooper et al's NHS surveillance study from June 2020 to March 2021 supports this, with nosocomial infections in HCWs primarily acquired from patients and other HCWs, with asymptomatic and pre-symptomatic transmission thought to be widespread (Cooper et al. 2023). Consequently, the wearing of face masks by HCWs and patients would appear an obvious IPC measure to take.

210. Having said this, demonstrating that masks are actually effective at inhibiting the transmission of SARS-CoV-2 has proven to be a somewhat challenging task (Walport & RS Working Group 2023). Since the start of the Covid-19 pandemic numerous studies have attempted to demonstrate the efficacy of respirators, surgical masks, and facemasks in general (e.g., (Boulos et al. 2023; Cheng et al. 2021b; Haller et al. 2022; Hunter & Brainard 2024; Leung et al. 2020; Wilson et al. 2020)). The evidence acquired from these studies adds to a large body of evidence that already existed prior to the pandemic on the use of face coverings in hospitals (e.g., (Booth et al. 2013; Gawn et al. 2008; Milton et al. 2013)). Because facemasks assist in blocking a known transmission pathway, they should potentially be effective in mitigating SARS-CoV-2 transmission. However, effectiveness can be compromised by numerous confounding factors such as, removing masks in order to eat and drink, the type of mask used, and its fit (Knobloch et al. 2023). These and other confounding factors have the effect of obscuring things, making it difficult to interpret the epidemiological data. This is especially so, given that the data was collected in the middle of a pandemic, when lockdown rules, testing and other IPC measures kept changing; all of which can severely compromise epidemiological studies and randomised controlled trials (RCTs).

211. Historically, medical professionals have placed much emphasis on RCTs when evaluating evidence. This has meant that when evaluating the effectiveness of non-pharmaceutical interventions (NPIs) such as face masks and hand hygiene, they have tended to rely heavily on RCTs and have downplayed evidence from observational, laboratory and modelling studies, with for example, the 2023 Cochrane review of NPIs using only data from RCTs (Jefferson et al. 2023). This approach has been criticised as being too restrictive, because it omits a vast body of non-RCT evidence (Bar-Yam et al. 2023; Greenhalgh et al. 2022; Greenhalgh et al. 2024a), and it has been highlighted as being unsuitable in situations such as pandemics where a precautionary approach is needed and ***"urgent decisions are required with limited evidence"*** (Muller 2021). Furthermore, with respect to the prevention of infection in hospitals, RCTs are notoriously difficult to conduct for a host of operational and ethical reasons, with results often compromised by the multiple confounding factors (Cash-Goldwasser et al. 2023; Dancer & Inkster 2022). Therefore, very few RCT studies exist that specifically relate to facemask usage in healthcare facilities, with most relating to use in the community (Chou et al. 2020; Chu et al. 2020; Jefferson et al. 2023; Solberg et al. 2024). In addition, because of the confounding factors outlined above, the evidence produced by RCTs regarding facemasks has been very mixed and inconclusive. Indeed, in a clarification statement concerning the findings of the 2023 Cochrane review, the Editor-in-Chief of the Cochrane Library stated: ***"Given the limitations in the primary evidence, the review is not able to address the question of whether mask-wearing itself reduces people's risk of contracting or spreading respiratory viruses."*** (Soares-Weiser 2024)

212. These difficulties were recognised by the Royal Society expert group evaluating the efficacy of NPIs (published in August 2023) (Walport & RS Working Group 2023), who stated: ***"In general,***

evidence drawn solely from RCTs has not yielded firm conclusions about the effectiveness of masks in reducing transmission, whereas a large volume of observational studies suggests, with low to moderate confidence, that masks are effective in reducing transmission." As such, this group highlighted the fallacy of relying solely on evidence from RCTs when evaluating IPC interventions. They also specifically criticised the application of the widely used GRADE system when reviewing IPC related evidence (Walport & RS Working Group 2023). This is because in the GRADE system, ***"RCTs are viewed as the 'gold standard' and application of GRADE criteria to other types of study design, including observational studies, means that these can only achieve a lower score and are classified as 'lower methodological quality or biased."*** (Walport & RS Working Group 2023) The group also said: ***"Using tools that evaluate behavioural interventions as if they are pharmaceutical interventions does not adequately embrace the complexity and variation in high-quality NPI observational studies. This strict stance can wrongly lead to claims that, given a lack of RCTs, there is no evidence and hence no action should be taken."*** (Walport & RS Working Group 2023) This highlights a much-overlooked issue that for many years has greatly hindered IPC research, and is the principal reason why in the Covid-19 pandemic the WHO dismissed much of the laboratory, modelling and animal experiment evidence supporting the aerosol transmission of SARS-CoV-2 (Lewis 2022; Morawska et al. 2023).

213. When reviewing evidence concerning the transmission of SARS-CoV-2 and the use of face masks, the systematic and rapid reviews produced before and early on in the pandemic, should be viewed with caution, because these were based on limited and often flawed information (as highlighted in Part 2). By comparison, studies undertaken later in the pandemic tend to be more reliable, because the evidence base was by then more extensive and robust. Given this, we report here the findings of the comprehensive review and meta-analysis undertaken in 2023 by the Royal Society expert group evaluating the efficacy of face masks (Boulos et al. 2023; Walport 2023; Walport & RS Working Group 2023). This review examined 35 recent studies (i.e., undertaken since 2020) in community settings (three RCTs and 32 observational studies) and 40 in healthcare settings (one RCT and 39 observational). Importantly, 95% of studies included in the Royal Society review were conducted before the Omicron variants emerged. This is highly relevant because, a recently published (May 2024) review (with meta-analysis) by Hunter and Brain (Hunter & Brainard 2024) revealed marked changes between the Delta and Omicron strains with regard to the impact of facemasks in the community.

214. The Royal Society review [71, 75, 80] found that the majority of studies reported that masks (n=39/45; 86.7%) and mask mandates (n=16/18; 88.9%) reduced infection compared with those that found no effect (n=8/66; 12.1%). Furthermore, detailed analysis of a subset of 26 studies (see Figure 17), found overwhelming evidence that mask wearing led to a reduction in SARS-CoV-2 transmission in community (13/14 comparisons; 92.9%) and healthcare settings (11/12 comparisons; 91.7%).

215. A further seven observational studies found that respirators (FFP2, FFP3 and N95) were more protective than surgical masks; five found no statistically significant difference between the two mask types, and two studies found increases in transmission, though these were not statistically significant. From this the Royal Society expert group concluded that, ***"the weight of evidence from all studies suggests that wearing masks, wearing higher quality masks (respirators), and mask mandates generally reduced the transmission of SARS-CoV-2 infection."*** (Walport & RS Working Group 2023) Having said this, they added the important caveat that most studies in the review were observational and could therefore have been more confounded (Walport & RS Working Group 2023).

216. Although the findings of the Royal Society review agree with those of many studies undertaken since the start of pandemic (e.g., (Chu et al. 2020; Ferris et al. 2021; Greenhalgh et al. 2024a; Kim et al. 2020; Ueki et al. 2022; Wilson et al. 2020)), it is noticeable that they are at variance with other studies, particularly those undertaken before the pandemic, which largely focused on the transmission of influenza and relied heavily on evidence from RCTs (Chou et al. 2020; Jefferson et al. 2023; Long et al. 2020; MacIntyre et al. 2013). The reasons for this discrepancy are discussed at length by Greenhalgh et al. (Greenhalgh et al. 2024a) who found the use of medical masks in community settings, to be associated with a significantly lower incidence of influenza-like illness or COVID-like illness (RR 0.89, 95% CI 0.87–0.91).

217. The evidence evaluated in the Royal Society review (Walport & RS Working Group 2023) was largely conducted before the highly transmissible Omicron variants emerged in late 2021. However, in a recent (May 2024) review (with meta-analysis), Hunter and Brainerd (Hunter & Brainard 2024) analysed the impact of mask wearing in the community on the transmission of SARS-CoV-2, both before and after the second Omicron variant (BA.2) emerged. This revealed a marked difference between these two periods. Prior to Omicron BA.2 (which emerged in February 2022), never wearing a facemask was associated with an approximately 30% increased risk of SARS-CoV-2 infection in adults, whereas after Omicron BA.2, the protective effect from mask wearing appeared to disappear completely (Hunter & Brainard 2024). While the reasons for this are unclear, it is important to remember that the cloth and disposable facemasks often used by the general public provide minimal protection against inhalation of fine aerosol particles. Also, it has been shown that facemasks like this are generally less effective at higher viral loads (Cheng et al. 2021b). Therefore, this might be the reason why such masks were found to be ineffective against the transmission of Omicron BA.2. If this is the case, then it might suggest that the aerosol route is more important in the transmission of Omicron BA.2, than for previous variants. However, we cannot be certain of this, because by February 2022, many people who did not wear masks had acquired some immunity (either through vaccination or contracting Covid-19), and therefore this could be the reason that mask wearing was less protective. By then, many travel and lockdown restrictions had also been lifted, both in the UK and overseas, with people adjusting to 'living with Covid', all of which profoundly altered behaviour and could have influenced the results of Hunter and Brainerd's review (Hunter & Brainard 2024).

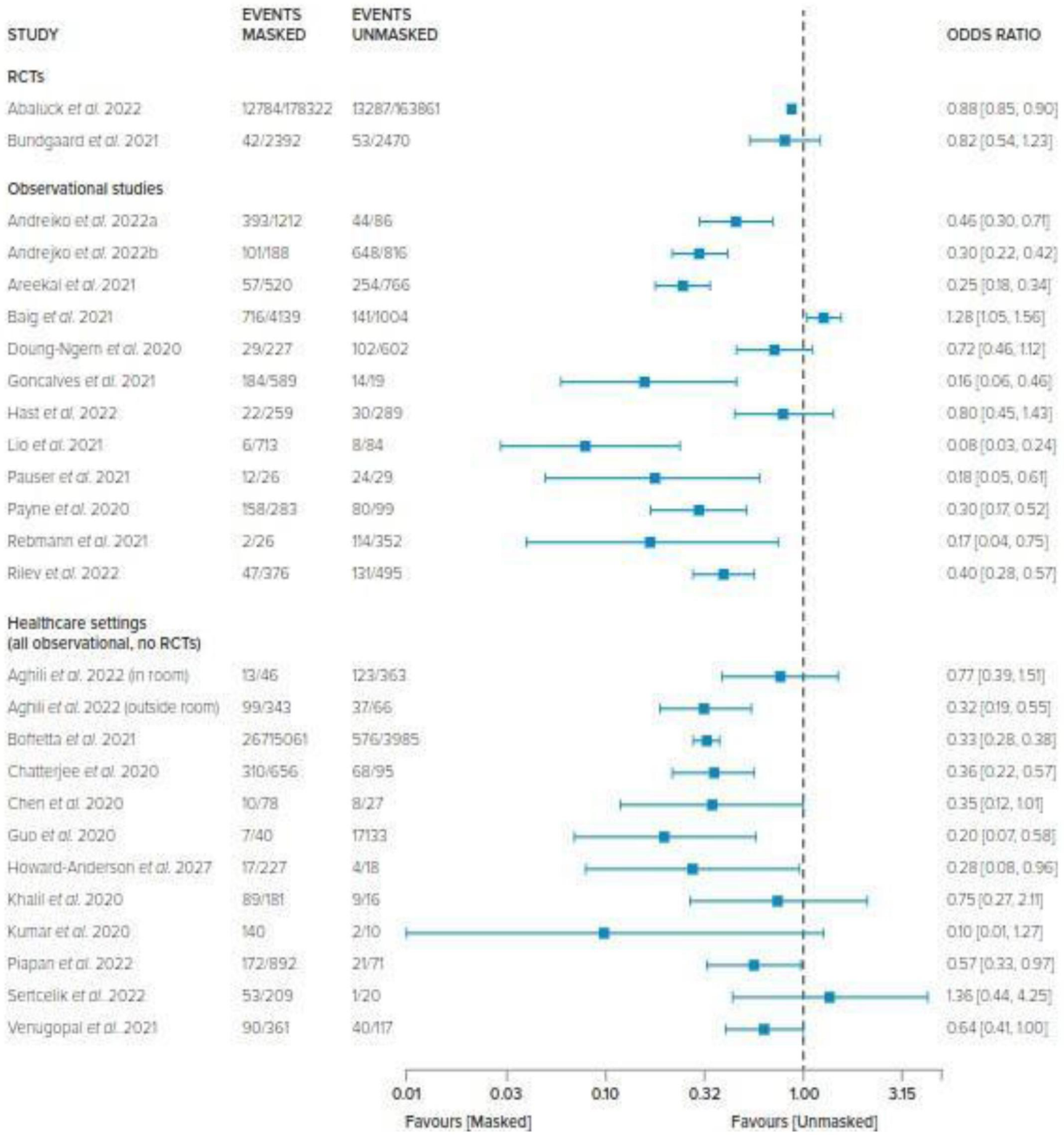


Figure 17. Forest plot taken from [71, 75] summarising outcome of studies comparing masked and unmasked subjects. (NB. The forest plot summarises the outcomes of studies that compared SARS-CoV-2 infection in people or groups of people classified as either wearing or not wearing masks. The plot contains those studies for which published data permitted the calculation of odds ratios and 95% confidence intervals. Average values (denoted by a blue square) of less than one mean that the study found that masks reduced infection. Confidence intervals (denoted by the horizontal blue lines) with the upper limit <1 are deemed to be statistically significant. This means that we can be confident that the observed reduction is likely to be real.

218. With regard to the specific issue of respirators and surgical masks, the Royal Society review states: ***"There is also evidence, mainly from studies in healthcare settings, that higher-quality 'respirator' masks (such as N95 masks) were more effective than surgical-type masks."*** (Walport & RS Working Group 2023) This conclusion agrees with Ferris et al. (Ferris et al. 2021) who in a study on a Covid-19 ward, found FFP3 respirators to be associated with a 52–100% reduction in the risk of HCWs acquiring a SARS-CoV-2 infection, compared with surgical masks. By contrast, Kunstler et al. (odds ratio = 0.85, [95% CI 0.72, 1.01]) (Kunstler et al. 2022), Haller et al. (adjusted hazard ratio = 0.8, 95% CI 0.6–1.0) (Haller et al. 2022) and Jefferson et al. (risk ratio = 0.82, 95% CI 0.66, 1.03) (Jefferson et al. 2023) all reported that it was unclear whether or not respirators performed better than surgical masks. However, close inspection of statistical analysis performed by these groups reveals that they all found respirator masks to perform better than surgical masks, although in each case the results did not quite reach statistical significance. (NB. Technically, in order to be judged significant, the upper limit of the confidence interval (CI) must be <1.) So, although all three groups were technically correct in saying that the results were unclear, (according to strict interpretation of statistical significance), this is a little misleading because in each case there was a clear trend toward significance. So, collectively, the results obtained by Kunstler et al. (Kunstler et al. 2022), Haller et al. (Haller et al. 2022) and Jefferson et al. (Jefferson et al. 2023) are arguably consistent with the overall findings from the Royal Society expert group (Walport & RS Working Group 2023). Indeed, given that many confounding factors would have influenced the results of these studies, the fact that these studies achieved results that either reached significance or were very close to it, suggests that there are good grounds for believing that respirators generally perform better than surgical masks at protecting HCWs against SARS-CoV-2. This opinion concurs with meta-analysis by Greenhalgh et al. (Greenhalgh et al. 2024a) (published May 2024) who reanalysed all the RCTs that compared N95 respirators (regardless of whether they were used intermittently or continuously) with surgical masks in health-care settings and found that the incidence of influenza-like illness was significantly lower in the N95 arm (RR 0.80, 95% CI 0.65–0.99).

219. Having said this, there is evidence that respirator masks are better suited to some applications than others. Cheng et al. (Cheng et al. 2021b) showed that the effectiveness of surgical masks is dependent on the viral load in the air, with masks tending to perform poorly in virus-rich environments. By comparison however, respirator masks performed much better when virus concentrations in the air were higher. Consequently, FFP2/FFP3 respirators are likely to be more effective in environments where the viral load is higher, such as COVID-19 wards, which may explain why Ferris et al. (Ferris et al. 2021) observed such a large beneficial effect when FFP3 respirators were introduced. Interestingly, Haller et al. (Haller et al. 2022) also observed that FFP2 masks were more protective amongst HCWs who had frequent exposure to >20 COVID-positive patients (adjusted hazard ratio = 0.7 for positive swab, 95% CI 0.5–0.8), from which they concluded: ***"Respirators compared to surgical masks may convey additional protection from SARS-CoV-2 for HCWs with frequent exposure to COVID-19 patients."*** (Haller et al. 2022)

Surgical masks or respirators?

220. Realisation that SARS-CoV-2 can be transmitted through the air (Duval et al. 2022; Miller et al. 2021; Morawska et al. 2023; SAGE-EMG 2020b) has caused many to reappraise whether or not FFP2/FFP3 respirators should be used more frequently by HCWs, which is the reason why a number of studies have been undertaken to compare the effectiveness of mask types. While there

is little doubt that facemasks can help to mitigate SARS-CoV-2 transmission, and that the performance of respirators is superior to that of surgical masks under controlled laboratory conditions (Ueki et al. 2022; Wilson et al. 2020), questions still remain over what happens in real-life. This is because factors such as ill-fitting masks, and taking masks off when in social or non-clinical contexts (Dancer 2021), can severely compromise their effectiveness. Nonetheless, from the evidence presented above a consistent picture emerges, namely that facemasks are likely to inhibit the transmission of SARS-CoV-2 in healthcare settings, and that respirator masks appear to afford superior protection to HCWs compared with surgical masks.

221. Although the evidence in support of facemasks is relatively robust, it appears that performance is influenced by the viral load to which HCWs are exposed, with the infection risk increasing as the viral load in the air increases (Cheng et al. 2021b). This led Cheng et al. (Cheng et al. 2021b) to conclude that while surgical masks might provide sufficient protection when exposure levels are low, in virus-rich environments, such as on Covid wards, they may not be adequate. From a physical science point of view, this makes complete sense, because the gaps around surgical masks can cause the wearers to inhale many more virus particles than would be the case with close fitting respirators, especially in poorly ventilated, virus-rich environments. Cheng et al's conclusion is supported by the finding of Haller et al. (Haller et al. 2022) that FFP2 respirators appear to be more effective, compared with surgical masks, when HCWs attend multiple Covid-positive patients. **It is also consistent with the findings of Ferris et al. (Ferris et al. 2021), who observed that while working on Covid wards, HCWs wearing surgical masks faced an approximately 31-fold increased risk of acquiring a ward-based SARS-CoV-2 infection, compared with those working on non-COVID-19 wards. However, after changing to FFP3 respirators, this risk greatly reduced (i.e., 52 to 100% reduction).**

222. Over the course of the Covid-19 pandemic, scientific thinking on when respirators should be used in preference to surgical masks gradually evolved. However, this evolution was slow. As late as May 2021, the joint recommendations the British Infection Association (BIA), Healthcare Infection Society (HIS), Infection Prevention Society (IPS) and Royal College of Pathologists (RCPath) (Bak et al. 2021) largely reflected the position for influenza before the pandemic, stating: ***"For care of patients suspected or confirmed to have COVID-19, ... use fluid resistant surgical face mask and adhere to contact and droplet precautions. No other precautions are necessary."*** In particular, this guidance stressed the central role of AGPs in transmission of SARS-CoV-2: ***"Literature suggests that most SARS-CoV-2 transmissions from patients to HCWs occurred when a HCW did not use protection during AGPs on patients not suspected of having COVID-19. Consider using filtering respiration mask (FFP3) designed for filtering fine airborne particles for any AGPs regardless of a patient's COVID-19 status when local assessment suggests risk of SARS-CoV-2 circulating in the community or local setting."*** (Bak et al. 2021)

223. However, by April 2022 when the NHS NIPCM for England (NHS-England 2022) was published, this guidance had subtly changed to: ***"Respiratory protective equipment (RPE), i.e., a filtering face piece (FFP) must be considered when a patient is admitted with a known/suspected infectious agent/disease spread wholly or partly by the airborne route and when carrying out aerosol generating procedures (AGPs) on patients with a known/suspected infectious agent spread wholly or partly by the airborne or droplet route."***

224. The language used in this long sentence in the NIPCM guidance is rather ambiguous and confusing, making implementation of the guidelines difficult, as the meaning of ***"spread wholly or partly"*** is not clear. The guidance links to a table in Appendix 11a of the NIPCM, which lists

pathogens claimed to be spread by different routes. In this table, Covid-19 is listed as ***"Droplet/Airborne"***, as is measles. Yet, the respiratory protective equipment (RPE) recommended for Covid-19 is only FRSM for routine care, with FFP3 respirators or hoods reserved for AGPs. However, measles, despite having the same listed route of ***"Droplet/Airborne"***, requires FFP3 for all (including routine) clinical care. As such, there appears to be inconsistencies between the approach taken to these two 'airborne' diseases. It is noted (above the table in Appendix 11a) that with respect to care of Covid-19 patients, FFP3 respirators must also be worn ***"when deemed necessary after risk assessment"***. While this reliance on local risk assessments leaves some room for interpretation, it is still within the official guidance for HCWs performing routine care of confirmed Covid-19 patients to only wear FRSMs. For further details of the complex evolution over time in these guidelines, the reader is directed to the Inquiry's clinical expert report on IPC by Prof. Gould, Dr Shin and Dr Warne.

225. Evidence from Cooper et al's (Cooper et al. 2023) surveillance study highlights that asymptomatic and pre-symptomatic SARS-CoV-2 transmission is a major problem in UK hospitals, with undiagnosed Covid-19 among patients and HCWs a major driver of nosocomial infection during the pandemic. As such, this suggests that many inpatients with a SARS-CoV-2 infection remain undiagnosed, or are being diagnosed too late having transmitted the virus to others (Illingworth et al. 2021). So timely diagnosis is an issue of great importance. However, there are knock-on issues associated with this, because a whole raft of IPC activities (e.g., the need for a ward side room, potential contact tracing; specific therapies, etc.) come in once Covid-19 is a working diagnosis, all of which have resource and cost implications. With regard to masks, if HCWs are required to use respirators, rather than surgical masks, this would also have a cost implication, especially as fit testing is required for respirator masks. So, any policy changes regarding testing and diagnosis will likely incur substantial costs for the NHS, as well as increasing pressure on bed management. Similarly, any policy change making sufficient respirator masks available to HCWs who request them when not performing AGPs, etc., would have cost implications.

226. Asymptomatic transmission, alongside inadequate ventilation in many clinical and non-clinical spaces, means that HCWs wearing surgical masks (or no mask at all) may frequently be exposed to a virus-rich environment. Given that median emission rates of inhalable aerosol particles have been found to be 135 and 270 particles per second for breathing and normal talking, respectively (Alsved et al. 2020), it is not difficult to envisage that those working in close proximity to an asymptomatic person may be exposed to elevated SARS-CoV-2 levels.

227. So, when and where should respirators be used in preference to surgical masks? There is no simple answer to this question, because there is much that remains unknown, and robust data is still needed. For example, while correctly fitted FFP3 respirator masks with over-the-head straps offer superior protection to HCWs, they can be uncomfortable; something that would likely affect compliance levels if they were to be widely mandated. Such respirator masks are also associated with more adverse events (e.g., headaches, skin irritation, etc.) (Kunstler et al. 2022). As such, there is a trade-off between what might be desirable, and what is achievable in practice, with utility being an important factor in the type of facemask worn by HCWs, patients and visitors. With regard to this, because FFP masks with ear loops are not recommended in the NHS, as they would unlikely to pass a stringent fit test, it effectively means that in UK hospitals, HCWs are faced with a binary choice, FRSMs or FFP3 respirators with head straps. However, experimental research from the Max Planck Institute in Germany (Bagheri et al. 2021) (published December 2021) shows that wearing FFP2 masks with ear loops, if well fitted, can greatly reduce the exhalation and inhalation of infectious aerosols. Indeed, even loose fitting FFP2 masks with ear loops resulted in a 2.5-fold reduction in mean infection risk compared with surgical masks, while

well-fitting FFP2 masks with nosepiece adjustment produced a 30-fold reduction in risk (Bagheri et al. 2021). As such, this suggests that FFP2 masks with ear loops might be a useful third option, which although not as protective as FFP3 respirators, could nonetheless be effective because they are more comfortable, better tolerated and provide superior protection compared with FRSMs.

228. To optimise policy on IPC, there is a pressing need for research to better understand how respirators and surgical masks can be utilised to best effect in order to minimise the infection risk in hospitals, both under pandemic and non-pandemic conditions. Integral to this, is the need to explore all facemask options, to identify solutions that provide the optimum mix of protection, utility and comfort. With respect to this, FFP2 masks with ear loops may be an effective 'off-the-shelf' solution that satisfies the compromise between protection and utility required by HCWs in the NHS. Currently (August 2024), such masks are not recommended for use in the NHS, because they are not considered to provide a tight enough fit (Knobloch et al. 2023). However, they provide superior protection against inhaling and exhaling aerosols compared with FRSMs, which are loose and generally much more ill-fitting (Bagheri et al. 2021). Indeed, during the pandemic, Austria, Italy and the Czech Republic made the wearing of FFP2 masks with ear loops mandatory on public transport (Lozzi et al. 2022). Notwithstanding this, given the mounting evidence that SARS-CoV-2 can be transmitted by the inhalation of infectious aerosols, there is urgent need to investigate all available facemask technologies in order to establish optimum strategies for minimising infection risk in a range of healthcare settings.

229. Having said this, it is known that good ventilation and source control are able to substantially lower the viral load in air, and thus reduce the 'workload' on masks, increasing the apparent effectiveness of both surgical masks and respirators (Cheng et al. 2021b), as acknowledged in the SAGE report, *"Masks for healthcare workers to mitigate airborne transmission of SARS-CoV-2"* (published 9th April 2021), which placed good ventilation above the wearing of surgical masks in the hierarchy of controls (SAGE-HOCI 2021). Consequently, reducing the viral load in room air in wards and other high-use healthcare spaces should be a priority, as this will improve the efficacy of surgical masks in particular. Viral load can be reduced by improved ventilation (see Part 4), and by reducing at source the amount of aerosol exhaled into the air. As such, there is good reason to utilise facemasks to reduce the number of respiratory particles exhaled by patients, visitors and HCWs on wards. In theory, surgical masks can be effective as a source control measure, because they intercept larger droplets before they have a chance to evaporate (Cheng et al. 2021b). However, it is the fit of the masks that is probably the most important factor. Although the fabric of surgical masks will trap most large droplets and some smaller particles, any gaps around the mask will allow free passage of the tiniest respiratory particles into the atmosphere, thus compromising performance and increasing the viral load in the air.

Part 4: Ventilation and air cleaning

Key findings:

- Ventilation is the introduction of fresh air from outside into an indoor space to dilute and remove contaminants. It is distinct from movement of air within a space, and cleaning of air with filters or other technologies, though both can occur alongside ventilation. Ventilation can be natural (such as opening windows) or mechanical.
- Healthcare settings have used ventilation for decades, though its use for infection control (as part of the "hierarchy of controls") has generally been limited to specific settings such as operating theatres, and isolation facilities for a shortlist of pathogens deemed to be airborne such as TB and measles.
- The Covid-19 pandemic, and increasing evidence about airborne transmission, has led to increased attention on ventilation in healthcare settings and elsewhere.
- Many healthcare settings are poorly ventilated and do not meet current recommended thresholds. Upgrading ventilation to improve its effectiveness for infection control purposes is complex and costly.
- The effectiveness of ventilation can be measured using carbon dioxide monitoring. However, it is unclear how this technology can be utilised in the NHS to greatest effect.
- Ventilation in English healthcare facilities is governed by Health Technical Memorandum (HTM) guidelines, which were written before the Covid-19 pandemic. For general wards and non-clinical spaces, where SARS-CoV-2 transmission often occurs, these prioritise comfort, odour control and energy efficiency over infection control. These guidelines are outdated based on current understanding of airborne transmission and are in urgent need of updating.
- Where existing ventilation is not sufficient to provide adequate infection control - a need which will increase during a respiratory pandemic - supplementary measures can be used. These include portable air cleaners, upper-room UV lamps and far-UVC lamps. Portable air cleaners are relatively inexpensive and easy to deploy, and have most existing evidence and some supporting guidelines, but all three interventions hold significant promise.
- More research is needed on the ventilation of hospital wards and the use of supplementary air cleaning technologies to ensure that healthcare settings are ready for the next airborne pandemic.

230. In Part 4, the role of ventilation and air cleaning as interventions to reduce the transmission of respiratory viral infection in healthcare facilities is discussed, and the physical science associated with this explained. However, before investigating the key issues, by way of a preamble to familiarise the reader, we briefly outline here the context and constraints that frame discussion of this subject. This is important because there are many misconceptions about ventilation and air cleaning in hospitals that arise because of the multidisciplinary nature of the subject, which requires knowledge and understanding of engineering, microbiology and medicine. However, many IPC and engineering professionals only have a superficial knowledge of the subject, which

means that it is all too easy for people to fail to appreciate key issues that lie outside their area of expertise. Consequently, many misconceptions have crept into the guidelines associated with the ventilation of healthcare facilities, which have subsequently been exposed by the Covid-19 pandemic.

231. The whole subject of hospital ventilation is framed by the historical distinction made between the droplet and airborne routes of transmission, discussed in Part 2. However, due to scientific advances made during the Covid-19 pandemic, this distinction now appears too simplistic, and not fit for purpose, as highlighted in the recent (May 2024) WHO report, which states that SARS-CoV-2, influenza, TB and measles are all "transmitted through the air" (WHO 2024a). Yet, the current (August 2024) NHS Health Technical Memorandum (HTM) hospital ventilation guidelines (NHS-England 2021a; NHS-England 2021b) still utilise the old 'non-airborne' (which includes droplet spread) and 'airborne' disease classification system to determine the level and type of ventilation required, with only a select few diseases (i.e., TB, measles and chickenpox (DoH 2013)) defined as being transmitted by the airborne route. Noticeably, influenza and Covid-19 are not included on this list, and therefore according to the HTM are deemed not to required enhanced ventilation, despite the fact that for much of the Covid-19 pandemic, health authorities around the world were vigorously promoted ventilation as a public health measure to mitigate the transmission of SARS-CoV-2.

232. This has led to serious inconsistencies between the current HTM guidelines (NHS-England 2021a; NHS-England 2021b) and scientific evidence acquired during the Covid-19 pandemic. This of course is unsurprising, given that the HTM documents on specialist ventilation were largely prepared before the pandemic. To this end both HTM documents are prefaced by the statement: ***"This HTM was prepared prior to the COVID-19 pandemic … It has been reviewed against the known transmission evidence available at the time of publication (22 June 2021). Ventilation is one of many mitigations against the virus … The ventilation rates recommended in this document are likely to provide a lower risk environment for COVID-19 airborne transmission."*** Nevertheless, aspects of the HTM guidelines now appear out of date following the pandemic, especially in the light of some recent scientific advances in understanding that have been made about the transmission of respiratory viruses.

233. While with hindsight it might be easy to criticise the HTM hospital ventilation guidelines (NHS-England 2021a; NHS-England 2021b), it is important to remember that they were written before the Covid-19 pandemic using the scientific consensus that prevailed at that time. So, although the scientific consensus has now changed (see Part 2), the HTMs largely reflect the received wisdom that prevailed before the pandemic. The job of those writing the HTMs was to ensure that the guidelines reflected the received scientific consensus that prevailed at the time, which they did. Therefore, if the perceived risk of acquiring an airborne viral infection is not considered high on say a general ward and in a non-clinical area, the guidelines simply reflect this, and accordingly, specify that specialist or enhanced ventilation is not required.

234. Many people get confused by the terms: 'ventilation', 'air movement' and 'air cleaning', which all appear very similar and interchangeable. However, these terms refer to distinct and very different things, and failure to recognise this can lead to confusion and erroneous misconceptions. Actually, 'ventilation' specifically refers to the introduction of fresh air from outside to flush away bacteria, viruses, and other particles and smells from room spaces, as well as providing fresh air for breathing. This is separate and distinct from 'air movement', which is simply refers to the movement of air around and between room spaces. The distinction is important because many fans and air-conditioning systems (devices), simply push (recirculate) air around and don't

actually ventilate (i.e., introduce fresh air from outside) room spaces. However, many people don't recognise this, and may erroneously think, for example, that an air-conditioning unit is ventilating the room, when in fact, all it is doing is promoting air movement and recirculating air around the space. Such systems, far from being protective, can be harmful, because they can blow airborne pathogens (harmful bacteria and viruses) towards people, as highlighted by the Covid-19 outbreak in a restaurant in China (Li et al. 2021) and the large TB outbreak that occurred on a US naval vessel (Houk 1980). Finally, the term 'air cleaning' refers purely to the process by which air is cleaned. In the context of disease transmission, this is often used to describe portable air cleaning devices which are mounted in rooms. These recirculate the room air and clean it using a high-quality filter. Strictly speaking, these devices don't ventilation (i.e., provide fresh air for breathing, etc.), but rather, remove bacteria, viruses and particulate matter (PM) from the room air. So, although such devices do not ventilate room spaces, in effect they provide a sort of 'equivalent ventilation', which is why this term is often used in this context.

235. Because provision of adequate room ventilation has historically been considered an engineering matter, it has often been something of an after-thought to many IPC professionals, who instead, have tended to concentrate on measures such as hand hygiene, mask wearing and surface disinfection. Consequently, with relatively few exceptions (i.e., operating theatres, isolation facilities for TB patients, etc.) (DoH 2013; NHS-England 2021a), prior to the Covid-19 pandemic, ventilation had largely been relegated in the hierarchy of IPC interventions in general wards and non-clinical spaces. However, with the realisation that the aerosol transmission of SARS-CoV-2 (and potentially other respiratory viruses) is widespread in healthcare facilities (as discussed in Parts 2 and 3), has elevated the importance of ventilation (both in clinical and non-clinical spaces) as an IPC measure. Indeed, by reducing the viral load in room air it is not only possible to reduce the risk of infection by the aerosol route, but also, boost the protective effect of surgical masks (Cheng et al. 2021b) (as discussed in paragraphs 182 to 186). Accordingly, providing adequate room ventilation is now ranked higher than PPE (i.e., surgical masks) in the hierarchy of IPC controls (SAGE-HOCI 2021).

236. Unlike many infection control measures (hand hygiene, isolation and cohorting, masks, gloves, aprons, etc.), which require little or no structural changes to implement, ventilation systems are embedded in the fabric of hospital buildings and therefore cannot easily be upgraded at short notice. For example, increasing the capacity of a central mechanical ventilation system, involves upgrading the fans, ductwork, and heat exchangers, all of which have considerable cost and energy implications. Furthermore, because of other constraints (unsuitable or old buildings, required building work, time constraints, etc.), upgrading such systems may not be feasible, especially in the middle of a pandemic. Indeed, during the Covid-19 pandemic, in many situations all that could be done to increase ventilation was simply to open windows, which although helpful is limited by: wind direction; architecture and complexity of the ward space; and patient comfort considerations. As such, this meant that opening windows alone was not necessarily going to provide enough protection, and that additional 'rapid' supplementary air cleaning was required in hospitals, which could be deployed at short notice with minimum disruption. In response to this, some hospitals deployed portable ultraviolet (UV) and high efficiency particulate air (HEPA) filter air cleaners to protect patients and HCWs (Butler et al. 2023b; NHS-England 2023a; NHS-England 2023b).

Introduction to ventilation

237. Because Covid-19 can be transmitted by the aerosol route, there are a number of environmental interventions that can help to mitigate its spread. Chief amongst these is improved ventilation to

dilute the concentration of infectious aerosols in room air. Ventilation is the process whereby clean outside air is introduced into a room space to flush out any virus and other pollutants. Importantly, this does not completely remove all infectious aerosols from the room air, but rather, its aim is to dilute and reduce the concentration of aerosols in the air to a safe level. Generally, the better the ventilation (i.e. the more outside air that is introduced), the lower the concentration of SARS-CoV-2 virus and other pathogens in the room air.

238. Room ventilation is ineffective against large droplets >100µm diameter, which are heavy, behave ballistically and fall rapidly to the floor. Ventilation can only flush away and remove aerosol particles that are suspended in the air, as these travel with the air currents. With respect to this, room ventilation is generally only effective at mitigating the far-field infection risk, because it cannot remove aerosol particles in the near field (i.e., within about 2 meters). This is because the distances involved in in the near-field transmission are too short to allow normal room (dilution) ventilation to act. So, in IPC terms, room ventilation is a measure designed to mitigate the transmission of disease by the airborne route. **Therefore, there is an inherent inconsistency in saying that room ventilation is important, while simultaneously arguing that airborne transmission does not occur.** This is something that many fail to appreciate.

239. Ventilation systems in buildings can be either natural (e.g. opening windows) or mechanical (e.g. a central heating, ventilation, and air conditioning (HVAC) system), or a mixture of both (a mixed-mode system). Importantly, such technologies should only be considered ventilation systems if they introduce clean outside air into the room space. However, the extent to which such systems 'ventilate' is not always obvious. For example, many central HVAC systems recirculate a large proportion (up to 80%) of the room air, which means that their ability to truly ventilate is greatly reduced. However, in UK hospitals most central HVAC systems employed in clinical spaces are 'full fresh air', which means that their primary purpose is to ventilate using 100% clean outside air.

240. In order to quantify the amount of ventilation required to minimise the risk of airborne transmission in any given context, engineers use two generic metrics:

- **'Air changes per hour'** (ACH), which is the number of complete air changes (replacements of air) that will occur in one hour. So, for example, if a room space experiences 2 ACH, then the air in the space will be completely replaced twice in an hour. This assumes perfect mixing of the air within the room space, which in practice often does not occur. This is because stagnant regions can exist within room spaces, where air replacement rate is somewhat lower. Therefore, the ACH rate should be considered an ideal metric, which represents the average air replacement rate within any given room space.

- **'Fresh air rate per person'**, which is generally specified in terms of litres of fresh air per person per second. For example, in a school classroom containing 30 people, if a fresh air rate of 10 L/s per person is specified, then the required total ventilation rate would be 300 L/s (Dimitroulopoulou & Bartzis 2014).

241. While the metric ACH is useful, it has the disadvantage that it relates to the room itself, rather than the requirements of the people inside the room space. So, in some situations, particularly when large numbers of people are present in a single space, specifying only the air change rate can lead to under-estimation of the ventilation rate that is required to minimise risk of transmission. After all, a room containing 50 people will require more fresh air than the same room with just two people in it.

242. When performing ventilation calculations and assessing infection risk it is generally assumed that the air in the space is fully mixed. However, this is often not the case because pressure differences and room air convection currents can concentrate aerosols containing viral particles in specific locations within a room space (Beggs et al. 2024)*. Consequently, regions of high and low virus concentration may exist within the same room at the same time, with the result that some people may be at more risk than others. This is a phenomenon that is poorly understood, because it is affected by many factors, including the movement of individuals and the opening and closing of windows.

243. One way of determining whether or not the ventilation in a space is adequate is by monitoring carbon dioxide (CO_2) levels. In the UK, outdoor CO_2 levels are normally about 400 ppm (Helfter et al. 2011). Indoors, CO_2 levels are higher due to the exhaled breath of room occupants. So in well ventilated spaces, CO_2 levels will generally be in the region 500 – 1,000 ppm (Burridge et al. 2023). However, in poorly ventilated spaces this can rise to >3,000 ppm (Gil-Baez et al. 2021). SAGE guidance suggests that indoor CO_2 values below 800 ppm are indicative of a well ventilated space, whilst those consistently >1,500 ppm are likely to indicate overcrowding or poor ventilation (Burridge et al. 2023; SAGE-EMG 2020c). In response to the Covid-19 pandemic the *Chartered Institution of Building Services Engineers (CIBSE)* produced a ventilation guide (CIBSE 2021) (July 2021) which recommended a minimum ventilation air supply rate of 10 L/s/person of outside (fresh) air, and indicated that in most circumstances this would result in a maximum CO_2 concentration of 800-1000 ppm. In addition, the CIBSE Covid-19 ventilation guide states that in places where enhanced aerosol generation is likely, ventilation levels should be high enough to maintain CO_2 concentrations below 800 ppm, which the guide suggests as typically being in the range 10-15 L/s/person (CIBSE 2021).

244. With reference to healthcare facilities, during the Covid-19 pandemic a number of studies were undertaken to determine CO_2 levels in hospitals, and these have generally found concentrations in ward spaces to be well below 800 ppm (Butler et al. 2024; Kenarkoohi et al. 2020; Vosoughi et al. 2021)*. However, in ancillary and non-clinical spaces (e.g., waiting rooms, cafeterias, offices, conference rooms, etc.) in a US hospital, Ha et al. (Ha et al. 2022) found CO_2 levels to be generally higher, but still mainly <800 ppm. However, in a conference room and also in an office, they did observe CO_2 concentrations to exceed 1200 ppm. In the UK, a study involving two modern hospitals Wilson et al. (Wilson et al. 2024) found median [range] CO_2 levels to be 507 [252 – 2805] ppm in non-clinical areas, and 474 [379 – 1863] ppm in clinical areas. Other studies involving hospitals in Cambridge (Butler et al. 2024)* and Bristol (Jain et al. 2021) have observed similar levels of CO_2 in ward spaces. While we cannot be sure how representative these studies are of the UK as a whole, it would appear that for the most part, CO_2 concentrations in sampled hospitals were generally <800 ppm, although Wilson et al. (Wilson et al. 2024) did observe this threshold to be exceeded 14% of the time in non-clinical areas and 7% of the time in clinical spaces.

Hospital ventilation guidelines

245. The ventilation of healthcare facilities in England is governed (as of August 2024) by Health Technical Memorandum (HTM) 03-01 Part A (NHS-England 2021a) and Part B (NHS-England 2021b) **which although published in June 2021 were actually written before the Covid-19 pandemic, and as such, reflect the rigid 'airborne – non-airborne' framework that pertained at the time (as discussed in Part 2).** These two documents, which are advisory (i.e., not

mandatory), ostensibly deal with the specification and operation of specialist ventilation systems (e.g., operating theatres, isolation rooms, etc.) in hospitals. But in reality, they also cover the general ventilation of hospitals wards and ancillary spaces, and as such are the *de facto* guidelines used to specify ventilation systems in healthcare facilities in England. Ventilation in Scottish hospitals is governed by two documents SHTM 03-01 Parts A & B (NHS-Scotland 2022a; NHS-Scotland 2022b), which are similar to and mirror their English counterparts.

246. Because this report is primarily concerned the fundamental physical science underpinning ventilation as an IPC measure in the NHS, the focus here will be on the general approach taken to the ventilation of clinical and non-clinical spaces in the NHS guidance documents rather than concentrating on specific regulations. The aim here is to review the documents in order to established whether or not they are robust and fit for purpose, should another coronavirus or influenza pandemic occur in the future. As such, a broad-brush approach will be taken, highlighting major short-comings or inconsistencies that in the opinion of the author need to be addressed. For brevity the discussion will focus on the guidance for England, which is broadly similar to the approach taken in Scotland, Wales and Northern Ireland.

247. The current HTM 03-01 Parts A and B guidance superseded the old (2007) HTM 03-01 document (DoH 2007). So, for much of the Covid-19 pandemic (January 2020 to June 2021), guidance on hospital ventilation was provided by the 2007 HTM document, which was replaced in June 2021 by current HTM 03-01 guidelines. However, for all practical purposes, **the guidance in the 'old' and 'new' HTM documents is broadly the same, with both using the rigid 'airborne – non-airborne' framework;** albeit that the newer HTMs encourage greater use of natural ventilation in hospitals to conserve energy.

248. With respect to this, very few infectious diseases are considered in the guidance to be airborne, with only TB, measles and chickenpox specifically listed as such in Health Building Note (HBN) 04-01 Supplement 1 (Clause 2.9) (DoH 2013). Under the HTM guidelines, patients with diseases deemed non-airborne (which includes influenza and respiratory syncytial virus (RSV), both thought to be primarily spread by droplets, as was the SARS-CoV-2 for much of the pandemic, before it was reclassified as "droplet/aerosol" in NIPCM (NHS-England 2022)) are considered low-risk, and therefore safe to be nursed on general/acute wards with no specialist ventilation provided (NHS-England 2021a). **However, the 'not airborne' classification in the HTM is completely out-of-step with current WHO recommendations (WHO 2024a), which classify both influenza and SARS-CoV-2, along with TB, measles and MERS as being infections that are "transmitted through the air".** As such, the classification of influenza (and presumably Covid-19, although not mentioned in the HTM) as "not airborne", becomes non-sensical in the light of the scientific advances and the change in position of the WHO and CDC that occurred during the Covid-19 pandemic. Specifically, the recognition that SARS-CoV-2 can be transmitted in inhalable aerosol particles by the WHO (WHO 2024a) and CDC (CDC 2024a), implicitly means that both these organisations accept, at least in part, that Covid-19 can be airborne. This is because aerosol particles by definition remain suspended in air and can travel far further than 2 meters. Therefore, the 'airborne' or 'not airborne' classification system used in the current HTM documents is out of date and in need of revision, so that it better reflects current scientific thinking.

249. Broadly speaking, these HTMs (NHS-England 2021a; NHS-England 2021b) classify spaces within hospitals as being either: (a) areas where the risk of 'airborne' infection is high and therefore specialist ventilation is required; or (b) areas where the airborne infection risk is low and therefore general building ventilation will suffice. Accordingly, specialist ventilation for infection control purposes is only deemed necessary in a few clinical contexts (e.g., operating theatres, isolation

rooms, day surgery, treatment rooms, 'clean' rooms, critical care, immunosuppressed wards, etc.) where the airborne risk of infection is perceived to be high, and it is on these areas that the HTMs focus.

250. Consequently, at the start of the pandemic, guidance was primarily focused on measures aimed at preventing the spread of diseases such as TB, and infections associated with AGPs such as bronchoscopy and endoscopy. In comparison, the airborne infection risk on acute and general wards (as well as in non-clinical areas) was considered to be low, and the IPC role of ventilation in these areas accordingly downplayed, with HTM 03-10 Part A stating (Clause 4.22): ***"In general areas and wards within healthcare premises, odour control is the main reason for providing ventilation"*** (NHS-England 2021a).

251. Outside of specific high-risk areas (e.g., operating theatres, isolation rooms, intensive care units, bronchoscopy suites, etc.), where specialist ventilation is deemed to be necessary, the HTM guidelines consider the risk of acquiring an airborne infection, on an acute or general ward, to be low, with HTM 03-01 Part A stating (Clause 1.7): ***"Most healthcare staff are no more at risk from airborne hazards when at their workplace than they are when not in a healthcare environment"*** (NHS-England 2021a). Similarly, when commenting on the airborne risk posed to patients, HTM 03-01 Part A states (Clause 1.10): ***"In general terms an environment that is satisfactory for staff will be satisfactory for patients".*** However, with subsequent evidence that respiratory aerosols are a major route by which SARS-CoV-2 is spread (Morawska et al. 2023; WHO 2024a), and that asymptomatic transmission is thought to be widespread (Gandhi et al. 2020; Hu et al. 2020), these assumptions have been shown to be incorrect. Indeed, Cooper et al (Cooper et al. 2023) concluded that there is an urgent ***"need for measures that reduce transmission from patients with asymptomatic infection in non-COVID-19 hospital areas, including improved ventilation, ..."***. Furthermore, they found that during the period June 2020 to March 2021 the vast majority of SARS-CoV-2 infections experienced by HCWs were acquired in hospitals from patients and other HCWs (Cooper et al. 2023), implying that during the pandemic, the risk of acquiring an airborne infection while working in a hospital was considerably greater than when outside in the community.

252. In the HTMs (NHS-England 2021a; NHS-England 2021b) areas deemed to require specialist ventilation include isolation rooms, operating theatres, critical care wards, and spaces where AGPs are undertaken, such as bronchoscopy and endoscopy suites. For brevity, the complexities of the prescribed ventilation systems for each of these areas are not described here; rather, in this section we focus on the ventilation of acute and general wards and non-clinical spaces, as these are the locations where the transmission of SARS-CoV-2 is most likely to occur.

253. For areas deemed at low risk from airborne infection, which include acute and general wards, ancillary and non-clinical spaces, the major concerns in the HTMs (NHS-England 2021a; NHS-England 2021b) appear to be: providing a comfortable environment; controlling odours; and minimising energy consumption, rather than controlling infection. In these spaces the guidelines encourage the use of natural ventilation through opening windows, where possible. However, it is recognised that because of the architecture and complexity of many hospital spaces that natural ventilation is not always possible. External noise and pollution levels can also compromise natural ventilation systems. In such circumstances, a mixture of mechanical and natural ventilation is recommended, with the mechanical ventilation generally provided by a ducted full fresh air system, which supplies and extracts air through vents (diffusers) in the ceiling. Supplementary natural ventilation is generally provided by windows around the perimeter of wards, which can be opened or closed at the discretion of HCWs.

254. Irrespective of size and occupancy levels, the HTM (NHS-England 2021a) stipulates that acute and general wards should be ventilated at a rate of 6 ACH, with ward toilets negatively pressurised and ventilated at 6 ACH (NHS-England 2021a). Ward side rooms should be either neutral or negatively pressurized and ventilated to 6 ACH. The HTM also specifies a minimum fresh air requirement of 10 L/s per person.

255. While stipulating an overall air change rate for general ward spaces, the HTM (NHS-England 2021a) says very little about airflow patterns within ward spaces themselves, save for stating that there should be a general hierarchy of cleanliness in which patients who are vulnerable to infection should be placed in positively pressurised environments, and those with an airborne infection placed in negatively pressurised environment (DoH 2013; NHS-England 2021a). However, patients with diseases deemed 'non-airborne' can be treated in neutral environments such as ward side rooms.

256. One noticeable feature of both HTMs (NHS-England 2021a; NHS-England 2021b) is they concentrate on operating theatres, isolation rooms, critical care units, and a few other specialist areas, with general wards and non-clinical spaces treated very much with a 'light touch'. This is true not only for the design of such systems, but also for their operation and maintenance, with HTM 03-01 Part B (NHS-England 2021b) drawing a clear distinction between critical healthcare ventilation systems (i.e. serving operating theatres, isolation rooms, etc.) and general ventilation systems for general wards and non-clinical spaces. In particular, critical healthcare ventilation systems require a quarterly visual inspection and annual verification to ensure that they perform to a specified standard, whereas general ventilation systems only require an annual visual inspection. Consequently, there is no guarantee that ventilation systems serving general wards and non-clinical areas (i.e., spaces where much SARS-CoV-2 transmission occurred) are actually delivering the air change rates specified in the HTM (e.g., 6 ACH).

257. Evidence would suggest that actual ward ventilation rates are often well below those specified in the HTM (Butler et al. 2024; Butler et al. 2023b; Dancer et al. 2022; Loh et al. 2023). For example, in a study at Addenbrooke's Hospital, Cambridge, Butler et al. (Butler et al. 2024)* found delivered mechanical ventilation rates to be 0.96 and 0.73 ACH on two medicine for the elderly wards, which was well below the 2.5 ACH in the original 1970s design specification for the ward mechanical ventilation, and far below the 6 ACH recommended in HTM 03-01 Part A (NHS-England 2021a). Also, experiments conducted on a naturally ventilated Nightingale ward observed ventilation rates that varied between 3.4 and 6.5 ACH (Gilkeson et al. 2013). As such, this latter study highlights an inherent problem associated with naturally ventilated wards, namely, that the ventilation rate can vary considerably, depending on the direction and speed of the wind.

258. From the discussion above it is clear that there are major inconsistencies between the state-of-the-art scientific knowledge (post Covid-19 pandemic) and the current HTM ventilation guidelines. **Furthermore, the HTMs do not reflect the fact that provision of good ventilation in wards and non-clinical spaces is part of the hierarchy of IPC controls, being ranked higher than PPE (i.e., surgical masks) (SAGE-HOCI 2021).** This is primarily because the guidelines were written before the pandemic and use the old 'airborne - non-airborne' paradigm that is based on an out-of-date understanding of the behaviour of droplets and aerosols (see Part 2). **Consequently, the guidelines do not reflect the risk of airborne (aerosol) transmission of SARS-CoV-2 and other respiratory viral infections in general ward spaces and non-clinical areas.** In particular, the key role of ventilation in protecting HCWs on wards and in staff areas is not addressed. Similarly, the use of ventilation to mitigate viral transmission between patients on

general wards is not discussed. **Therefore, the current HTM guidelines cannot be considered fit for purpose in these respects.**

Key issues not covered in the HTM ventilation guidelines

259. The Covid-19 pandemic has raised many important issues that are not adequately covered in the current HTM guidelines on hospital ventilation, and which need to be addressed. Chief amongst these is the whole issue of what constitutes an airborne infection risk, especially given that much SARS-CoV-2 transmission involves asymptomatic individuals [65-67]. Therefore, in addition to defined AGPs, there needs to be recognition that when breathing or talking, patients and HCWs can potentially be transmitting viral infection by the aerosol route. Accordingly, performance specifications for the ventilation of general clinical and non-clinical spaces need to reflect this fact.

260. There is a need for guidance regarding airflow patterns to mitigate the spread of infection by the aerosol route in general clinical and non-clinical spaces. The current HTM guidelines (NHS-England 2021a) only specify air change rates for general clinical and non-clinical spaces, and say nothing about air movement within or between those spaces. However, there is increasing evidence that infectious aerosols can migrate considerable distances around wards due to convection currents and pressure gradients (Butler et al. 2023a; Butler et al. 2023b)*, especially when hospital wards are open plan, which could potentially undermine the effectiveness of patient isolation and cohorting strategies. Furthermore, infectious aerosols can become concentrated in stagnant regions (Beggs et al. 2024)* or trapped in circulation vortices (Butler et al. 2023a; Butler et al. 2022)*, exposing patients and HCWs to increased risk of infection. In particular, aerosols can become concentrated in ward side rooms, or on one side of patient bays (Butler et al. 2023a)*, with the result that patients adjacent to an infectious patient are likely to be exposed to higher aerosol concentrations, compared with those opposite (Butler et al. 2023a; Li et al. 2007)*. Accordingly, recommendations need to be incorporated into the HTMs giving guidance regarding airflow patterns to mitigate the spread of infection by the aerosol route in general clinical and non-clinical spaces.

261. The HTM guidelines (NHS-England 2021a) recommend, where possible, the use of natural ventilation. While openable windows are an excellent low energy way to boost ventilation of hospital buildings, they cannot be relied on alone to provide adequate ventilation in deep or complex spaces, or during periods of high occupancy. Also, they can result in the formation of uncomfortable cold draughts, especially during the winter months, as well as allowing fine particulate matter (PM) to enter ward spaces from outside, something that potentially can have a negative impact on the respiratory health of patients and HCWs. However, from an IPC standpoint, perhaps the more serious drawback associated with windows is that the ventilation rates achieved can be highly variable, depending on wind speed and direction. The HTM guidelines do not address this issue, or suggest how minimum ventilation rates can be maintained when windows are closed due to noise and comfort requirements.

262. Although the HTM guidelines (NHS-England 2021b) are very rigorous regarding verification of ventilation rates in perceived high-risk areas such as operating theatres and negatively pressurised isolation rooms, much less attention is paid to the validation of ventilation rates in perceived low risk areas like general ward spaces, outpatient waiting areas, and staff rooms, etc. For these spaces the HTM recommends only an annual visual inspection (NHS-England 2021b). Therefore, actual ventilation rates achieved in such spaces may be well below that specified in

the HTM guidelines (NHS-England 2021a). For example, Butler et al. (Butler et al. 2023b)* found that measured ventilation rates on a medicine for the elderly ward in an English hospital were well below the 6 ACH specified in the HTM guidelines (Butler et al. 2024). Similar findings have been observed in Scottish hospitals (Dancer et al. 2022; Loh et al. 2023). Given, this there is urgent need in the HTMs to extend the scope of the validation process to include more rigorous verification of ventilation rates achieved in general clinical and non-clinical spaces.

263. Since the COVID-19 pandemic, CO_2 concentration has increasingly been used as a surrogate marker for ventilation in buildings (Bain-Reguis et al. 2022; Burridge et al. 2023; Di Gilio et al. 2021; Lyu et al. 2023; Villanueva et al. 2021; Wilson et al. 2024). Ventilation air introduced from outside dilutes the exhaled CO_2 produced by building occupants, and so the CO_2 concentration can be used to determine whether or not a space is adequately ventilated. SAGE guidance suggests that indoor CO_2 values below 800 ppm are indicative of a well ventilated space, whilst those consistently >1,500 ppm are likely to be indicative of poor ventilation (Burridge et al. 2023; CIBSE 2021; SAGE-EMG 2020c). Studies undertaken in hospitals in the UK (Butler et al. 2024; Jain et al. 2021; Wilson et al. 2024) and overseas (Ha et al. 2022; Kenarkoohi et al. 2020; Vosoughi et al. 2021) have generally found CO_2 concentrations in clinical and non-clinical spaces to be below 800 ppm. While this suggests that the sampled hospitals were generally well ventilated according to this criterion, it nonetheless raises questions about whether: (i) 800 ppm is the correct threshold to use in healthcare facilities; and (ii) CO_2 monitoring has a role to play the NHS. Notwithstanding this, it is noticeable that, save in the context of energy conservation, the current HTM guidelines do not consider the use of sensors to monitor CO_2 concentration in clinical and non-clinical spaces. This omission looks rather incongruous, given the both SAGE and CIBSE have made recommendations on the subject, albeit not specifically in the context of healthcare. Therefore, it is recommended that the subject of CO_2 levels and monitoring be considered (or at least mentioned) in future revisions of the HTM guidelines, given its high profile.

264. Similarly, the current HTM guidelines do not mention supplementary air cleaning, which during the Covid-19 pandemic was sometimes deployed in NHS to combat the transmission of SARS-CoV-2 (Butler et al. 2023b) (see paragraphs 268 to 289 for further details). Guidance on the use of portable supplementary air cleaners was eventually produced by the NHS in May 2023 (NHS-England 2023a; NHS-England 2023b). However, this was very much an 'add-on' produced in response to the pandemic. Consequently, there is need to tie these additional guidance notes into the HTM documents, so that the subject of supplementary air cleaning is covered in a coordinated and comprehensive manner.

265. Finally, there is no mention in the current HTM guidelines about strategies for future pandemics and emergencies, where for example, wards might need to be repurposed for isolation and cohorting purposes, as frequently happened during the Covid-19 pandemic. This is a complex issue, which from a ventilation point of view presents a considerable challenge, because it is not easy the alter mechanical ventilation systems that have been 'hard-wired' into the fabric of buildings. Nonetheless, it is an important topic which needs consideration, if hospitals are to be robust enough to cope with future pandemics. While it is beyond the scope of this report to discuss this topic in detail, it may be supplementary air cleaning systems have an important role to play in protecting patients and HCWs in future pandemics.

266. From the discussion above it can be seen that many issues highlighted by the Covid-19 pandemic are not adequately covered in the current HTM ventilation guidelines, and this is something that needs to be addressed, with appropriate policies and solutions formulated.

Interventions used to supplement ventilation

267. During the Covid-19 pandemic, additional ventilation could often be provided by simply opening windows. Although helpful, this is limited by: wind direction; architecture and complexity of the ward space; and patient comfort considerations. As such, this meant that opening windows alone was only ever a partial solution, and that there remains a need for additional supplementary ventilation in hospitals that could be deployed at short notice with minimum disruption.

268. There are several technologies that could be used to help with this. This section of the report mainly covers **portable air cleaners**, powered by a fan, that clean or disinfect air with a filter or UVC light and then recirculate it. Portable air cleaners are generally floor standing (see Figure 18) and can be deployed quickly and easily, without major modifications to hospital infrastructure. During the pandemic, these devices were deployed by several hospitals in the UK to protect patients and HCWs (Butler et al. 2024; Butler et al. 2023b; Noakes et al. 2023; Wilson 2023)*. However, towards the end of this section, other technologies are also covered briefly: a more established method using **upper-room UV lamps**, which disinfects air that has risen in thermal plumes to near ceiling level, before the air then cools down and returns to breathing level; and the emerging technology of **far-UVC lamps**, that shines UV light at a specific wavelength across the whole room to disinfect airborne pathogens. Both these technologies are permanent (fixed) systems that are generally mounted on walls or ceilings, and therefore require infrastructure modifications. It should be noted that there are also fixed versions of portable air cleaners, which can be permanently mounted on walls and ceiling if so desired.

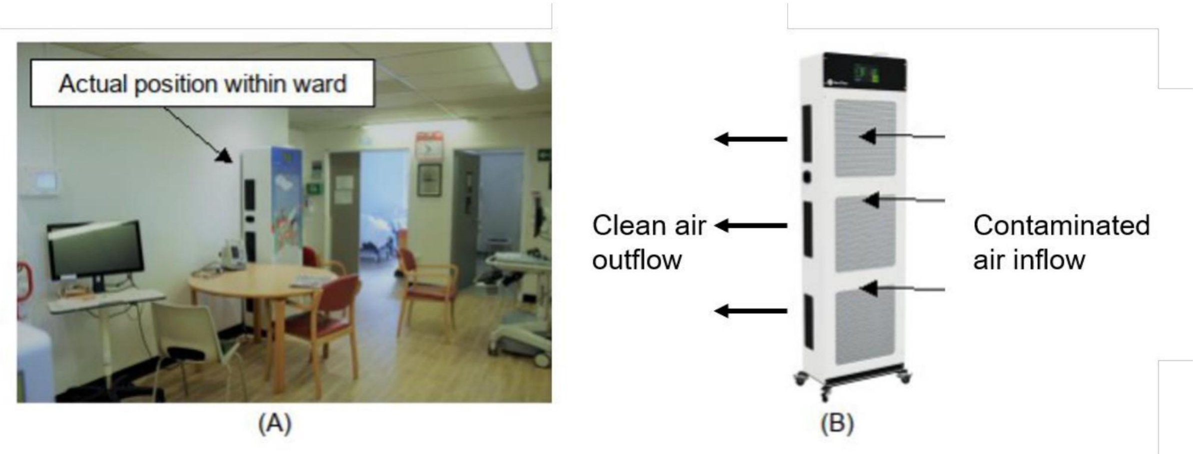


Figure 18. Portable air cleaning device used in the AAirDS study, showing: (A) location on ward; and (B) detail of device showing air inlets and outlets.

269. Portable interventions to supplement existing ventilation potentially have a role in ensuring robustness against future influenza, coronavirus, and other respiratory pathogen pandemics. When considering pandemic preparedness, a balance needs to be struck between ventilation requirements during pandemic (or epidemic) conditions and those required for everyday use (i.e., when there is no pandemic). This presents a major engineering challenge, because ventilation rates considered adequate during non-pandemic conditions, may be inadequate during a pandemic, when the viral load in the air on wards is likely to be much higher. Mechanical ventilation systems are costly pieces of infrastructure that are expensive to run. As such, it is prohibitively expensive to install oversized equipment which may only be run at full capacity

occasionally during pandemic conditions. So, flexible engineering solutions are needed that can cope with the peak demand of future pandemics, while still being capable of being down-rated for normal use. With respect to this, one approach that has great potential is the use of portable air cleaning devices, which remove virus particles from room air, and which can be rapidly deployed as required. These can be deployed throughout hospitals to increase effective ventilation rates. Furthermore, supplementary room air cleaners have the great advantage that they are relatively inexpensive and can be easily deployed, without the need for any renovation or building work.

270. Most supplementary air cleaners are room-mounted devices that employ either a high efficiency particulate air (HEPA) filter or an ultraviolet (UVC) lamp within the device to clean or disinfect the air. The difference between the two is that HEPA filter devices actually remove aerosol particles from the air, whereas UVC lamps destroy the genetic material in the SARS-CoV-2 virus, rendering it incapable of infecting individuals. HEPA filters and UVC lamps can also be employed in central HVAC systems. However, the efficacy of supplementary air cleaning is dependent on many factors, including the size of the device and how it is deployed. Consequently, much remains unknown about the efficacy of such devices against SARS-CoV-2, or indeed, how they should be deployed to best effect.

271. During the Covid-19 pandemic, provision of adequate ventilation became a high priority (SAGE-EMG 2020c; SAGE-EMG 2020d). With this came recognition that better ventilation was urgently required in hospitals, particularly for general clinical and non-clinical spaces, where transmission of SARS-CoV-2 infection was likely to occur. However, as explained above, this presented a major engineering challenge because mechanical ventilation systems cannot easily be up-rated to increase ventilation capacity. Aware of this, the SAGE Environment and Modelling Group published a report on the 4th November 2020 titled: *"Potential application of air cleaning devices and personal decontamination to manage transmission of COVID-19"* (SAGE-EMG 2020a), which endorsed the use of portable air cleaners to provide supplementary 'ventilation' in spaces that were poorly ventilated.

272. In response to this, some hospital authorities started to install portable air cleaners to provide supplementary 'ventilation'. However, this was undertaken on an ad hoc basis because there were no guidelines on: (i) the type of air cleaner that should be deployed; (ii) the size and number of the air cleaning units that should be deployed; or (iii) where the air cleaners should be located to optimum effect.

273. Notwithstanding this, there was good reason to believe that supplementary HEPA filter air cleaners and UV air disinfection devices might be effective in reducing SARS-CoV-2 transmission in hospitals (Barnewall & Bischoff 2021; Beggs & Avital 2020; Conway Morris et al. 2021a; Curtius et al. 2021)*. Therefore, during the pandemic some hospitals in the UK deployed portable air cleaners in wards as a precautionary measure, even though at the time there was a lack of epidemiological evidence to support their use. This meant that supplementary air cleaning units were installed in hospitals, without any guidelines to inform their deployment, or any attempt made to validate their performance. Therefore, in order to 'rapidly' acquire evidence and provide guidance the following studies were commissioned in the UK:

- **AAirDS study:** Comprehensive study of the performance of UV/HEPA filter air cleaning units on a medicine for older people ward at Addenbrooke's Hospital, Cambridge; commenced 2022. (Butler et al. 2024; Butler et al. 2023a; Butler et al. 2023b)*

- **AFRI-c study:** Comprehensive study of the performance of HEPA filter air cleaning devices involving 74 care homes; commenced 2021. [https://fundingawards.nihr.ac.uk/award/NIHR129783]
- **Class-ACT study:** Comprehensive study of the performance of HEPA filter and active UV air cleaning units in 30 primary schools in Bradford; commenced 2021. (Noakes et al. 2023; Wilson 2023)*

274. The author of this report was a member of the teams that conceived, designed and conducted the AAirDS and Class-ACT studies, and therefore has intimate knowledge of these projects. Unfortunately, these studies did not commence until late 2021 or 2022, which meant that the epidemiological findings from some of these studies have not yet been formally reported, although initial results are encouraging (see paragraphs 275 to 280 for full details). However, the final report on the AAirDS project has been submitted to the UKHSA (Butler et al. 2024)* and a number of scientific papers arising from the study are currently (August 2024) in preparation.

Evidence supporting the use of portable air cleaners

275. The scientific principles underpinning HEPA filtered air cleaning and UVC air disinfection devices are firmly established and have been validated in numerous laboratory studies, which have shown that these technologies can successfully remove or inactivate viruses (e.g., (Barnewall & Bischoff 2021; Biasin et al. 2021; Eickmann et al. 2020; Ueki et al. 2022). Similarly, devices incorporating these technologies have been shown to reduce viral and bioaerosol load in the air in controlled chambers (Beswick et al. 2023; Parhizkar et al. 2022; Ueki et al. 2022). For example, Ueki et al. (Ueki et al. 2022) showed that a HEPA filter device (with a high effective air change rate) could greatly reduce (i.e., >99%) the concentration of SARS-CoV-2 in the air of a test chamber. In another study, Parhizkar et al. (Parhizkar et al. 2022) placed people diagnosed with Covid-19 in a test chamber, and showed that with a HEPA filter air cleaner present the concentration of SARS-CoV-2 RNA in the air was reduced. **So, there is no doubt that these technologies can be remove or inactivate SARS-CoV-2 virus particles under controlled laboratory conditions.**

276. While there is good laboratory data demonstrating that air cleaning devices can be effective, there is a paucity of high-quality evidence regarding the effectiveness of portable air cleaners in real-life situations, and especially in the clinical context. However two rapid reviews, Bowles et al. (Bowles et al. 2022) (posted as a pre-print 26th October 2022) and Brady et al. (Brady et al. 2023) (posted as a pre-print 6th October 2023) have been undertaken, evaluating the evidence for the use of portable HEPA filter air cleaners. Although, these studies currently (June 2024) remain preprints, during the pandemic Bowles et al. (Bowles et al. 2022) was influential and informed the preparation of the NHS Estates Technical Bulletin: NETB 2023/01A (NHS-England 2023a). Both rapid reviews evaluated evidence relating to the application of HEPA filtered and enclosed UV devices in real-life settings, with their overall findings generally being positive. For example, Bowles et al. (Bowles et al. 2022) concluded that ***"Real world evidence suggests supplementary air systems have the potential to reduce SARS-CoV-2 in the air and subsequently reduce transmission or infection rates ..."***, and Brady et al. (Brady et al. 2023), while more ambiguous in their findings, did conclude that **"*... HEPA filters and natural ventilation are the most effective methods to reduce PM levels*".** However, both these studies were greatly hindered by a lack of homogeneity in the studies that were reviewed, making it very difficult to come to firm conclusions.

277. In a study undertaken at Addenbrooke's Hospital, Cambridge, Conway Morris et al. (Conway Morris et al. 2021a) showed that lower levels of SARS-CoV-2 RNA in the hospital ward air were associated with the use of supplementary HEPA filter air cleaners. Also, in another study at the same hospital, Butler et al. (Butler et al. 2023b)* showed that the action of supplementary HEPA air cleaners filtered (which also incorporated a supplementary UV lamp to disinfect the filters) greatly reduced particulate matter (PM) levels in ward air.

278. The full epidemiological findings from the AFRI-c and Class-ACT studies have yet to be formally reported. However, initial results from the Class-ACT study suggests the action of the air cleaners was associated with a 48% reduction in airborne particulate matter (Noakes et al. 2023)*. Furthermore, initial reports suggest that the HEPA filter air cleaners reduced COVID-19 related absences by more than 20% in the schools in the Class-ACT study (Wilson 2023).

279. The findings of the AAirDS study were recently (June 2024) reported to the UKHSA (Butler et al. 2024)*, which found that the action of the air cleaners was associated with 44% and 29% reductions, respectively, in airborne particulate counts ($PM_{2.5}$) on the two study wards over approximately a year. It also found that the air cleaners were associated with a lower microbial (i.e., bacteria, virus and fungi) burden in air, floor and worktop surface samples (all statistically significant), but not in samples from a sink. With regard to the epidemiological findings, over an extended period, there was a 22% reduction in the number of SARS-CoV-2 infections on the intervention wards, although this failed to reach significance (HR 0.78, 95% CI 0.53 to 1.14). While these are encouraging results, it is important to note that during the study the air cleaning units were frequently switched off or unplugged by the staff on the wards. So, the reported results likely underestimate the potential benefits derived from installing the devices. This highlights one major weakness of portable air cleaning devices, namely, that they can easily be switched off by HCWs, thus nullifying any potential benefits.

280. **Collectively, the evidence presented above suggests that supplementary air cleaning devices have the potential to reduce the airborne viral load in hospital wards, and potentially mitigate the transmission of SARS-CoV-2 infection.** However, while this is encouraging, much remains unknown about how such devices should be deployed in healthcare facilities to best effect.

Guidance on the use of portable air cleaners

281. In the absence of any guidelines regarding the deployment of supplementary air cleaning devices, the SAGE Environment and Modelling Group published a report on the 4th November 2020 titled: "*Potential application of air cleaning devices and personal decontamination to manage transmission of COVID-19"* (SAGE-EMG 2020a). This endorsed the use of portable air cleaners to provide supplementary 'ventilation' in spaces that were poorly ventilated. However, while the SAGE report gave useful information regarding the principals involved in air cleaning and the factors that affect performance, together with guidance regarding the technologies that should be used, no practical guidelines were given regarding the number and size of devices required for any given application, or specific guidance given about where such devices should be deployed.

282. In May 2023 two Technical Bulletins were published by NHS England, "NHS Estates Technical Bulletin (NETB 2023/01A): application of HEPA filter devices for air cleaning in healthcare spaces: guidance and standards" (NHS-England 2023a), and " NHS Estates Technical Bulletin (NETB 2023/01B): application of ultraviolet (UV-C) devices for air cleaning in occupied healthcare

spaces: guidance and standards" (NHS-England 2023b). These documents were published just as the Covid-19 pandemic emergency was officially declared over by the WHO (WHO 2023). As such, they obliquely highlight some of the shortcomings in the current ventilation HTMs (NHS-England 2021a; NHS-England 2021b), which were written before the pandemic. Specifically, NETB 2023/01A (NHS-England 2023a) states: ***"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."*** In saying this, the Technical Bulletin echoes many of the sentiments highlighted above in this report. The Technical Bulletin then goes on to say: ***"Local HEPA filter-based air cleaners (also known as air scrubbers) are one option for improving and supplementing ventilation"***, highlighting that portable air cleaners may have an important role to play in mitigating the transmission of viral infections in healthcare facilities.

283. Importantly, the Technical Bulletins are the first NHS documents to offer any practical guidance regarding the deployments and application of HEPA filter and UV air cleaning devices in hospitals. In addition, the HEPA filter document, NETB 2023/01A (NHS-England 2023a) acknowledges that sometimes ventilation rates may fall below those specified in the HTM 03-01A (NHS-England 2021a), especially when relying on openable windows to provide adequate ventilation, because these can be problematic when the weather is cold or it is noisy outside. In such circumstances, the use of portable HEPA filter air cleaners is suggested as ***"one option for improving and supplementing ventilation."***

284. However, in NETB 2023/01A (NHS-England 2023a) no guidance is given regarding the location within room spaces that HEPA filter devices should be placed in order to achieve optimum results. All the guidance is couched in the terms of achieving specified air change rates, with no regard given to the impact of the air cleaner on airflow patterns within room spaces. However, work undertaken during the AAirDS study has shown the placement of air cleaners on wards can have a significant impact of the flow of airborne pathogens within and between patient bays (Butler et al. 2023a)*.

285. While NETB 2023/01A (NHS-England 2023a) offers useful technical information regarding the application of HEPA filter air cleaners, it is always in the context of providing supplementary equivalent ventilation to restore ventilation rates to those specified in HTM 03-01A (NHS-England 2021a), which are by inference considered adequate. No mention is made of using air cleaners to go over and above the HTM 03-01A specified ventilation rates in the event of another pandemic.

286. A welcome inclusion in NETB 2023/01A (NHS-England 2023a) is the requirement to validate and verify the continued performance of the any HEPA filter air cleaners that may be installed.

287. The NETB 2023/01B guidelines (NHS-England 2023b) for UV air disinfection systems mainly cover so-called 'active' UV devices, in which the UVC lamp is enclosed. These devices can be portable or permanently fixed. Although, this technology does not filter the air, this type of UV device ostensibly behaves in a very similar manner to HEPA filter air cleaners, with the UV lamp mounted in an enclosed box, which has a circulating fan. Consequently, much of NETB 2023/01B mirrors NETB 2023/01A (NHS-England 2023a). Having said this, UV devices work in a completely different manner to HEPA filters, in so much that they don't filter the air; rather they use high-energy photons, generally at 254 nm, to damage the genetic material of the virus (or bacterium or fungus) so that it cannot replicate and cause an infection (Beggs 2002)*.

288. As with NETB 2023/01A (NHS-England 2023a), the guidelines in NETB 2023/01B (NHS-England 2023b) give little clear guidance as to how and where UV air disinfection devices should be used to best effect. This is understandable, given that much remains unknown about application and deployment of air cleaning devices in general.

289. So, in summary, while NETB 2023/01A and NETB 2023/01B provide some helpful guidance regarding the deployment of supplementary air cleaning devices, there is much that remains unknown about how they should be applied to best effect.

Other ultraviolet light devices to supplement ventilation

290. In addition to active UV systems, which incorporate a fan, there is another UV technology that potentially may help mitigate the transmission of airborne pathogens, namely, passive upper-room UVC air disinfection (Beggs & Avital 2020; Escombe et al. 2009; Noakes et al. 2015; Zhu et al. 2013)*. This is an old technology, which was used in the 1930-1960s to successfully combat the transmission of TB (Escombe et al. 2009) and which is claimed to be safe if applied correctly (Nardell et al. 2008). It involves creating an open UVC (wavelengths 254 nm) irradiation field above the heads of room occupants (Figure 19) to disinfect aerosolised bacteria and viruses circulating in the room air (Beggs & Avital 2020; Beggs et al. 2006; Beggs & Sleigh 2002; Noakes et al. 2015)*. Because UV light at 254 nm is harmful to humans (it can cause irritation of the skin and eyes), such systems utilize baffles that obscure the UV lamps from eyesight so that room occupants are safe. As such, upper-room UV is a well-established technology (First et al. 1999a; First et al. 1999b) that has proven effective as a public health intervention to prevent the spread of airborne diseases such as measles (Nardell & Nathavitharana 2019) and tuberculosis (TB) in buildings (Escombe et al. 2009; Noakes et al. 2006b).

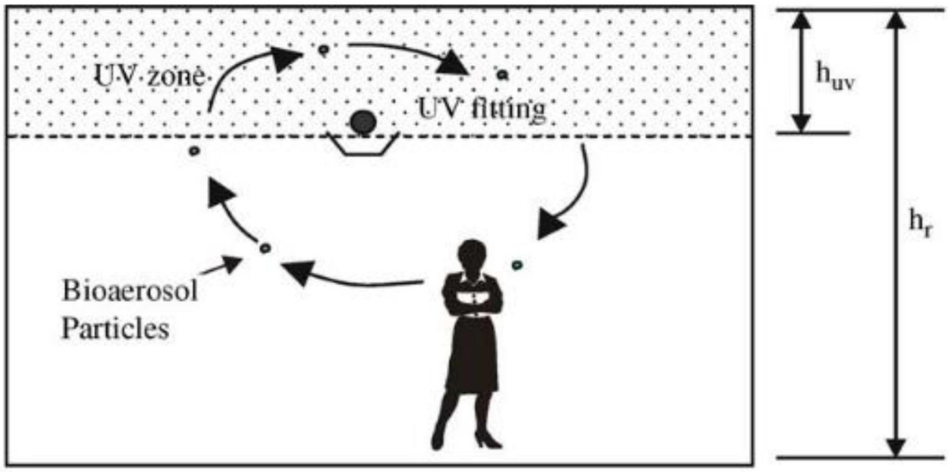


Figure 19. An upper-room UV air disinfection installation, showing the circulation of bioaerosol particles passing through the UV irradiation zone above the heads of the room occupants.

291. One major advantage of upper-room UV is that it can be retrospectively fitted into buildings provided that the floor to ceiling height is large enough to ensure that the UV field does not impinge

on room occupants (First et al. 1999b). By installing such as system it is possible to effectively 'turbo-charge' the existing the ventilation system. Depending on the strength of the UV field and whether or not a ceiling fan is used, some have suggested that it might be possible to achieve equivalent air change rates >80 ACH using upper room UV (McDevitt et al. 2008). However, this value appears very optimistic, and perhaps a more realistic uplift (in the opinion of the author) would be in the region of an additional 10 AHCs, assuming no ceiling fan was used (Beggs & Avital 2020; McDevitt et al. 2008)*. Having said this, no real-life trials have been undertaken to evaluate the equivalent air change rates that would be achieved for SARS-CoV-2 or influenza in clinical setting, so we have to rely on modelling studies and theoretical calculations to evaluate the performance that might be achieved (Liu et al. 2023).

292. Many laboratory and modelling studies have also shown the effectiveness of upper-room UV against a variety of pathogens including SARS-CoV-2 (Beggs & Avital 2020; Noakes et al. 2004; Noakes et al. 2015; Zhu et al. 2013)*. For example, Liu et al. (Liu et al. 2023) in a CFD study based on a hospital setting, estimated that it should be possible to achieve >90% reduction in airborne SARS-CoV-2 levels using a UV field with relatively modest strength. In another CFD study in a dental setting, Yao et al. (Yao et al. 2024) found at a ventilation rate of 6 ACH, an upper-room UV system with an irradiation flux of 5 $\mu W/cm^2$ achieved a 70.44% average SARS-CoV-2 virus reduction in the whole room, which was equivalent to doubling the ventilation rate. However, upper-room UV remains unproven in UK hospitals and outstanding health and safety concerns about the open UV field employed by this technology need to be settled. Notwithstanding this, upper-room UV remains a promising technology, which requires evaluation in a clinical context to assess its efficacy as a potential tool against pathogen transmission.

293. Similar to upper-room UV, another passive system that utilises an open field is far-UVC, which is a new and largely untried technology that appears to have considerable potential (Buonanno et al. 2024; Eadie et al. 2022; Eadie et al. 2021; Wood et al. 2023; Wood et al. 2022). However, unlike upper-room UV, were irradiation takes place above the heads of people, with far-UVC the whole room is irradiated, without the need for the occupants to vacate the space. While this might appear unsafe, proponents of far-UVC claim that it is safe because the system uses UV light at wavelength 222 nm, which is less harmful than light at 254 nm. Much work has been done in recent years to evaluate the safety of far-UVC, and there appears now to be a body of work suggesting that the technology is relatively safe when used appropriately (Kousha et al. 2024; Panzures 2023), although some safety concerns still persist (Tavares et al. 2023).

294. Notwithstanding any safety concerns, the efficacy of far-UVC against a range of pathogens has been conclusively demonstrated (Buonanno et al. 2024; Eadie et al. 2022; Wood et al. 2022). For example, Buonanno et al. (Buonanno et al. 2024) found that a far-UVC system in an animal care facility reduced murine norovirus in the room air by 99.8%. Similarly, in a controlled room-sized chamber a similar system achieved a 98.4% reduction in airborne *Staphylococcus aureus*, providing an additional 184 equivalent ACH rate. The impressive nature of these results, strongly indicates that far-UVC has considerable potential. However, uncertainty regarding its safety, means that unlike upper-room UV, much work still needs undertaken before it can be safely deployed.

Part 5: Lessons learnt and recommendations

Key findings

295. In this report we have investigated the physical science underpinning the transmission of SARS-CoV-2 and influenza, and have focused in particular on the science associated with infectious respiratory particles of all sizes travelling through the air, as well as on the role of NPIs such as facemasks and ventilation in mitigating the risk of infection. We have also considered at length how the scientific thinking on this subject evolved during the Covid-19 pandemic, from a position in early 2020 that broadly asserted (albeit with notable dissenting voices) that Covid-19 was not airborne to one in 2022 where it was generally accepted that the inhalation of infectious aerosols is a major contributor to the spread of Covid-19.

296. The physical science associated with the transmission of infection has historically received much less attention compared with epidemiological evidence. **However, understanding the physical science is critically important, because it is a prerequisite that enables correct interpretation of animal and epidemiological studies to be undertaken.** All biological systems obey the laws of physics, and in this respect the transmission of infectious disease is no different. In order for infectious disease to spread from one person (or animal) to another a plausible route of transmission must exist. Therefore, it is necessary to correctly understand the physical mechanisms associated with the transmission of disease, in order to correctly interpret epidemiological data.

297. The physics of droplets and aerosols is complex, and has, over many years, frequently been misunderstood, or ignored, by those researching the transmission of respiratory viral infection (Randall et al. 2021). Consequently, by the mid-twentieth century erroneous misconceptions had become firmly embedded in the medical and microbiological scientific literature, which subsequently, have caused much confusion in the literature (WHO 2024a) and have proven very resistant to change. **Chief amongst these was the erroneous belief that so-called 'droplets' >5µm diameter behave ballistically and rapidly falling to the ground, travelling no further than about 1 to 2 metres. In fact, particles much larger than 5µm behave as aerosols, which remain suspended in the air, and not like ballistic droplets. As such, particles >5µm diameter can remain suspended in air for many minutes, and travel far further than 2 metres (Wei & Li 2015).** However, the opinions from dissenting scientists (often from physics and engineering (e.g., (Morawska et al. 2023; Tang et al. 2021a; Wei & Li 2015)) who showed that respiratory particles in this size range could be widely distributed within room spaces, were largely dismissed by the medical community, with the result that early in the Covid-19 pandemic the potential threat posed by infectious respiratory particles at distances greater than 2 meters was underestimated.

298. **There is no physical basis for the 5µm diameter threshold between 'droplet nuclei' and 'droplets'.** It is a completely arbitrary threshold that was made in the mid-twentieth century purely on the basis of clinical diagnosis, rather than any understanding of physics. In fact, respiratory particles much greater than 5µm, perhaps as large as 30µm, can be transported in room air currents, depending on their strength, and as such are technically aerosol particles. Droplets by definition are ballistic and cannot be suspended in air. In the context of exhalation, the only respiratory particles that behave as droplets are those >100µm diameter, which cannot evaporate enough before they hit the floor. All exhaled particles smaller than this rapidly evaporate to about

a third of their original size and become aerosol particles, which settle slowly and can be transported by air currents.

299. The erroneous belief that particles >5µm diameter are droplets and not aerosol particles has caused much confusion in the scientific literature, which persists until today (August 2024). This has caused misunderstandings to occur between scientists and clinicians, who may in some circumstances be referring to the same phenomenon, but be using very different terminologies. Indeed, the realisation that SARS-CoV-2 can be transmitted via aerosols has done little to clarify things, because all that has happened is that health authorities have just bolted the term "aerosol" on top of their existing guidelines, so that now Covid-19 is described as *"droplet/aerosol"*, with little consideration of what this actually represents (NHS-England 2022). Consequently, there is much confusion in the guidance. For example, in attempting the clarify the difference between airborne and droplet spread, the UKHSA appears to use the terms 'droplets' and 'aerosols' interchangeably, and wrongly states that: ***"Droplets ... can penetrate deep into the lungs"*** (UKHSA 2024). In fact, only small aerosol particles can penetrate into the lower respiratory tract. It is this confusion that eventually prompted the WHO (April 2024), in an attempt to correct things, to propose that the outdated terms "droplet" and "aerosol" be replaced by the catch-all term *"transmission through the air"*, which includes both pathogens in infectious respiratory particles that are either inhaled or impact directly on the mucosal surfaces of the nose, mouth and eyes (WHO 2024a). Importantly, the WHO recommended keeping the term "airborne" as a subset of *"through the air"* transmission, and highlighted that this route of transmission could occur over any distance (i.e., both in the near and far-fields). They also listed influenza amongst the pathogens that spread by this route alongside TB, measles, SARS-CoV-2, SARS and MERS, implying that all share similar behaviours.

300. The belief that particles >5µm could not travel further than 2 metres has been hugely influential, especially when coupled with the assumption that the vast majority (about 99%) of the exhaled viral load was contained in the so-called larger 'droplets' >10µm (PIP-Team 2011b; Weber & Stilianakis 2008). Based on these two assumptions, both of which now appear to be incorrect, the doctrine of **'droplet transmission'** emerged, which asserted that because the vast majority of the viral load is found in 'droplets' >5µm that cannot travel further than about 1-2 meters, the predominant route of transmission must therefore be via droplets impacting on the mucous surfaces of the eye, nose and mouth. By inference, this implied that airborne transmission was unlikely to occur, because only about 1% of the viral load was assumed (wrongly) to be in the small aerosol particles (i.e., so-called 'droplet nuclei'). **In fact, in recent years (since 2010), numerous studies involving influenza** (Bischoff et al. 2013; Coleman & Sigler 2020; Cowling et al. 2013; Kormuth et al. 2018; Lindsley et al. 2010b; Yan et al. 2018) **and SARS-CoV-2** (Alsved et al. 2023a; Coleman et al. 2022; Jaumdally et al. 2024; Tan et al. 2023) **patients have shown that the majority of the exhaled viral load is found in aerosol particles <5µm, which strongly suggests that key assumptions underpinning 'droplet transmission' are not correct.**

301. The assumptions outlined above were extremely influential in the interpretation of animal and epidemiological study evidence (PIP-Team 2011b). Many studies involving mice, ferrets and guinea pigs have shown that influenza can be transmitted through the air (Andrewes & Glover 1941; Belser et al. 2022; Mubareka et al. 2009; Richard et al. 2020; Sutton et al. 2014). However, it was not known to what extent this transmission was by droplets or aerosols. Given this doubt, those evaluating the evidence tended to fall back on the *a priori* assumption that the vast majority of the exhaled viral load was likely to be in the larger droplets. **Consequently, they assumed that droplets must be the predominant route of transmission, rather than aerosols (PIP-Team 2011b), and required a far more stringent standard of evidence when interpreting**

studies challenging this assumption than studies (and guidelines) agreeing with it, which could be argued as being a form of conformation bias. Likewise, the same assumption has been applied to the epidemiological evidence (PIP-Team 2011b), with the result that the airborne transmission of respiratory viruses was considered unlikely. However, in the light of strong evidence suggesting that most of the exhaled viral load is actually found in aerosol particles <5μm that can travel much further than 2 meters, this questions the interpretation of epidemiological and animal study data in the 2011 *"Routes of transmission of the influenza virus: scientific evidence base review"* (PIP-Team 2011b) and suggests that it may be flawed. Furthermore, given that infectious individuals exhale many thousands of aerosol particles per minute, much, much more than the number of large droplets produced, it means that the potential to infect others through the inhalation route, as opposed to landing on the mucosa of the eyes, nose and mouth, is greatly increased.

302. The implications of this thinking are far-reaching. For example, if most of the exhaled viral load is in the droplets, then there is good reason to believe that trapping exhaled droplets is more important than preventing the escape of respiratory aerosols. Consequently, surgical masks, which have gaps around the face, have historically been considered adequate for infection control purposes for most respiratory infections. However, if exhaled aerosols contain most of the virus, then trapping aerosols becomes an issue of great importance. **Consequently, the current reliance on loose fitting surgical masks as the primary NPI measure used by HCWs should be reconsidered, since this type of mask does not fully interrupt the inhalation and exhalation of fine aerosols.**

303. Similarly, if exhaled aerosols are an important transmission route for respiratory viruses, then provision of good ventilation in both clinical and non-clinical spaces becomes an issue of high priority, as SAGE EMG recognised (SAGE-EMG 2020a; SAGE-EMG 2020c). **Currently (July 2024), the NHS HTM guidelines for the ventilation of hospitals (NHS-England 2021a; NHS-England 2021b), which were written before Covid-19 pandemic, use an out-of-date 'non-airborne' and 'airborne' disease classification system to determine the type and level of ventilation that should be provided and as such, are no longer fit for purpose in the post-Covid era.** In particular, the HTMs do not recognise the risk posed by exhaled aerosols containing SARS-CoV-2 (as acknowledged in the NIPCM Appendix 11a (NHS-England 2022)) or, indeed, influenza, and instead focus mainly on the ventilation of operating theatres, isolation rooms, intensive care units, bronchoscopy suits, etc. By comparison, general wards and non-clinical spaces are given minimal attention, despite the fact that these are areas where much SARS-CoV-2 transmission occurred. Indeed, Clause 4.22 in HTM 03-10 Part A specifically states: ***"In general areas and wards within healthcare premises, odour control is the main reason for providing ventilation"*** (NHS-England 2021a), highlighting the mis-match between the guidelines and the science relating SARS-CoV-2 transmission.

304. Another consequence of the assumption that viral load is mainly concentrated in larger droplets is that during the Covid-19 pandemic it focused attention on the droplet contamination of fomites as a possible route of transmission. Indirect fomite transmission of SARS-CoV-2 was considered highly likely, and so, much attention and effort were focused on the disinfection of surfaces and washing of hands during the pandemic. **However, while hand hygiene and surface disinfection are important IPC measures, the evidence supporting fomite transmission of SARS-CoV-2 is surprisingly weak,** with the first epidemiological evidence showing a possible association between surface contamination and the risk of infection only appearing in April 2023 (Derqui et al. 2023). Although SARS-CoV-2 can remain viable on non-porous surfaces for many hours, it degrades much faster on porous surfaces (Van Doremalen et al. 2020b; Xu et al. 2023)

and on human skin (Hirose et al. 2021). Also, much of the viral load is lost or diluted through hand-to-surface and surface-to-hand (or indeed, hand-to-hand) contacts (Pancic et al. 1980), making this route of transmission less likely for respiratory viruses, as the authors of the 2011 PIP reports on influenza noted (PIP-Team 2011a; PIP-Team 2011b). Notwithstanding this, if the majority of the exhaled viral load is in the aerosols and not in large droplets, then it may be that droplet contamination of surfaces has been over-estimated.

305. While the extent to which respiratory droplets contaminate surfaces is not known, there is no doubt that widespread SARS-CoV-2 contamination of inanimate surfaces and objects occurred during the Covid-19 pandemic, because numerous studies recovered RNA from frequently touched surfaces in hospitals (Elbadawy et al. 2021; Moore et al. 2021; Zhou et al. 2023a; Zhou et al. 2023b). However, while this shows that SARS-CoV-2 RNA is frequently transferred to commonly touched surfaces, it does not mean that it is infectious, because is likely that most of the SARS-CoV-2 RNA detected was not viable. The same issue applies in many air sampling studies. Just because viral RNA is recovered from the air or a surface, it does not necessarily mean that it is viable and able to cause infection. **Having said this, unlike RNA recovered from surfaces, which is often hours or even days old, that recovered from the air is generally much younger (in most cases less than an hour old) and therefore potentially more likely to be viable. Indeed, the half-life of SARS-CoV-2 in air has been shown in experiments to be about 1.1 hours** (Van Doremalen et al. 2020b), **which implies that in room settings with ventilation rates greater than one air change per hour, there is a high chance that some of the SARS-CoV-2 RNA inhaled will be viable, especially if individuals spend several hours in the same space as an infectious person. Furthermore, because many aerosol particles that are inhaled are only seconds or a few minutes old, it means that the chance of inhaling viable RNA is much greater.**

306. **While good hand hygiene is important, the evidence that it substantially mitigates the transmission of respiratory viruses is relatively weak.** For example, although the 2023 Cochrane review of the impact of handwashing on the spread of respiratory viruses (Jefferson et al. 2023) found a 14% relative reduction in acute respiratory infections to be associated with improved hand hygiene, no statistically significant improvement was observed for influenza. **This led the Cochrane team to conclude that good hand hygiene was likely only to result in a modest reduction in the burden of respiratory illness**; an opinion that echoed the findings of the 2011 PIP report investigating hand hygiene and the transmission of influenza (PIP-Team 2011a).

307. Before the Covid-19 pandemic, evidence that asymptomatic people could transmit respiratory infections was mixed, with methodological differences between researchers producing widely differing results (Leung et al. 2015). So, with the onset of Covid-19, there was considerable uncertainty as to whether or not asymptomatic and pre-symptomatic individuals could infect others. **However, by September 2020 it was clear that asymptomatic transmission was widespread** (SAGE 2020b), particularly in children and young people. In particular, asymptomatic transmission was (and remains) a problem in the NHS, with transmission involving both asymptomatic patients and HCWs (Cooper et al. 2023; Illingworth et al. 2021). Without coughing or sneezing, such people can exhale many thousands of infectious virus particles per minute in respiratory aerosols when they breathe or talk (Chen et al. 2021a). As such, this highlights the need to provide good ventilation in staff rooms and non-clinical spaces, as well as on wards. Staff rooms in particular, appear to be places where transmission can readily occur, because they are often small intimate spaces that are poorly ventilated, in which HCWs talk, eat and drink.

308. One of the major unintended consequences of the historical 5µm threshold between droplets and droplet nuclei was that medical and IPC professionals tended to think that a binary divide existed between the two classes. However, this is not the case. Exhaled respiratory particles come in a wide range of sizes, with most being small and inhalable, <20µm, while a few can be >100µm. Furthermore, due to evaporation, once exhaled, all respiratory particles rapidly shrink in size to about a third of their original diameter. This means that most become tiny aerosol particles that can float in the air and travel considerable distance around rooms, far further than 2 meters. However, the largest droplets, >100µm, behave ballistically (like a stone being thrown) and quickly fall to the floor, traveling less than 2 meters.

309. Small respiratory aerosol particles can remain airborne for many minutes, with the result that in enclosed spaces the concentration of aerosols in the air can quickly build-up over time, particularly if the room is poorly ventilated. So, if an infectious person with Covid-19 is in a room, the viral load can quickly build-up in the room air, with the result that everyone in the room space is potentially at risk of acquiring an infection due to far-field exposure. However, individuals within 2 meters in front of the infectious person (i.e., in the direct path of in the exhaled aerosol plume) are more likely to be exposed to higher virus concentrations in the near-field. Accordingly, a distinction is made between near and far-field exposure.

310. Historically, the far-field infection risk has only been considered relevant to airborne diseases such as TB, which are caused by the inhalation of infectious aerosol particles <5µm (so-called 'droplet nuclei'). Over many years, scientists researching TB transmission have developed epidemiological models to estimate (predict) the risk of acquiring an airborne infection in the far-field, the most famous of which is the Wells-Riley model (Beggs et al. 2003; Nardell et al. 1991; Riley et al. 1978)*. However, because infections such as influenza, have historically been considered to be droplet-borne (as SARS-CoV-2 was also classified for much of the pandemic), it means that the far-field infection risk has been considered negligible, as was highlighted in the 2011 PIP report on the transmission of influenza (PIP-Team 2011b). This however, is not the case, because, regardless of the official classification of the disease, if the exhaled respiratory aerosols contain virus particles (as is the case with influenza (Bischoff et al. 2013; Coleman & Sigler 2020; Cowling et al. 2013; Kormuth et al. 2018; Lindsley et al. 2010b; Yan et al. 2018)), then the concentration of virus in the room air will inevitably build-up over time, thus presenting a far-field infection risk. **From this we can see that using the <5µm threshold to wrongly classify diseases as 'airborne' or 'not airborne', has had far reaching consequences on IPC policy, and resulted in some erroneous conclusions being reached, including the *a priori* assumption in early 2020 that SARS-CoV-2 was not an airborne disease. There was enough epidemiological and physical science evidence by September 2020 to overturn this assumption, especially when compared with the weaker evidence for other routes of transmission.**

311. The concentration of virus in room air depends on: (i) the quantity of virus exhaled; (ii) the length of time the infectious person spends in the room space; and (iii) the room ventilation rate. With respect to the viral load shed into the air, it has been shown that when people talk or sing, they exhale much more SARS-CoV-2 virus compared with when they are breathing normally (Alsved et al. 2023a). Also, the longer an infectious person stays in the room space, the greater the risk to others. Behavioural aspects are therefore very important to the risk of transmission. Finally, the concentration of virus particles in the air also depends on the room ventilation rate, with poorly ventilated spaces tending to have higher virus concentrations in the air. As such, this highlights with important role of ventilation in mitigating the airborne (aerosol) transmission of respiratory viral infections. This is something that SAGE EMG recognised relatively early in the Covid-19

pandemic, when they issued guidance promoting good room ventilation and the use of CO_2 monitoring (SAGE-EMG 2020c), as well as promoting the use of supplementary air cleaning devices in situations where ventilation is poor (SAGE-EMG 2020a).

312. The risk of an individual acquiring a SARS-CoV-2 infection appears to be proportional to the viral load inhaled, and therefore is simply a function of: (i) the concentration of virus in the inhaled air; and (ii) the length of time that the susceptible person is exposed to inhaling infectious aerosols. This appears to hold true for both near-field and far-field exposure. So, the risk of acquiring a SARS-CoV-2 infection can be mitigated by either reducing the concentration of virus in the air, or spending less time in the room space. While the former is generally recognised (hence the call for better ventilation), **the importance of exposure time is often forgotten, or not considered at all, which is potentially the case when infections are classified as being droplet-borne and the aerosol build-up in room air is ignored** (PIP-Team 2011b).

313. The NHS IPC guidelines (NHS-England 2022) place great emphasis on the use of FFP3 respirator masks to mitigate the risk of aerosol transmission when HCWs perform so-called AGPs. However, in comparison, **much less attention is paid to the risks posed by natural respiratory aerosols exhaled by patients, HCWs and visitors, despite the fact that these aerosols vastly outnumber those produced by AGPs, and potentially pose a greater infection risk.** When breathing and talking, people exhale hundreds of aerosol particles per second (Alsved et al. 2020), and so any HCW working in close proximity to an infectious person, be they a patient or another HCW, is likely to be exposed to elevated SARS-CoV-2 levels. This is especially the case when infectious individuals are asymptomatic or pre-symptomatic, because the exposure risk is not recognised. Given this, the imbalance in the IPC guidelines between the attention paid to AGPs and that given to exhaled aerosols is all the more noticeable.

314. While the evidence suggests that face masks help to mitigate the transmission of SARS-CoV-2 (Walport & RS Working Group 2023), surgical masks provide only limited protection against infectious aerosols. This is primarily because they are loose fitting, which means that during inhalation and exhalation, small aerosol particles can readily flow through the gaps between the mask and the face. The situation is made worse when surgical masks are worn incorrectly, or removed. So, while surgical masks are helpful at reducing the exhalation of droplets and large aerosol particles into room air, they offer only limited protection to the wearer against the inhalation of infectious aerosols. In order, to give full protection against inhalation of infectious aerosols, FFP3 respirator masks need to be worn. However, FFP3 respirators with head straps are uncomfortable and need to be fit-tested, which limits their utility. **So, there is need for alternative facemasks in the NHS that provide superior protection against aerosols, while still affording good utility. Possible alternative facemasks, such as FFP2 masks with ear loops, do exist with offer HCWs better protection compared with FRSMs** (Bagheri et al. 2021), **and the potential for using these in the NHS should be explored.**

315. The Covid-19 pandemic highlighted not only the need for good ventilation in hospitals, but also the fact that many spaces are poorly ventilated. However, upgrading hospital ventilation systems is an expensive and challenging task, because it generally involves substantial modifications to the hospital infrastructure. **Given this, the use of portable air cleaning devices to supplement existing ventilation systems appears to have great potential.** These devices, which employ HEPA filters or UVC lamps, are relatively low cost and can be rapidly deployed as required to boost effective air change rates. However, while the evidence suggests that they can be very effective at cleaning the air and reducing the viral and bacterial bioburden (Butler et al. 2024; Butler et al. 2023b; Conway Morris et al. 2021a)*, little is known about how they should be

deployed to best effect. **Similarly, fixed installations such as upper-room UV air disinfection and far-UVC have the potential to reduce the viral load in the air within hospitals, although epidemiological evidence supporting their use in healthcare facilities is lacking.** Also, in the case of far-UVC there are safety issues that need to be clarified before it can be utilised.

316. There is evidence that aerosol particles can easily move considerable distances around hospital wards on air currents (Butler et al. 2024; Butler et al. 2023b)*, with the result that regions of high aerosol concentration can occur (Butler et al. 2023a)*, which could potentially expose some patients and HCWs to higher viral loads. With respect to this, thermal plumes generated by people and heating devices (Beggs et al. 2024; Butler et al. 2023a)* appear to be influential in driving convection currents and aerosol movement in hospital wards.

317. During the Covid-19 pandemic, scientific understanding of the transmission of respiratory viral infections rapidly progressed. However, guidelines tend to lag behind the cutting-edge science, and of necessity are conservative. As a result, many guidelines, especially those relating to hospital ventilation, still reflect many out-of-date historical misconceptions regarding the transmission of respiratory infection.

Knowledge gaps

318. While many advances were made during the Covid-19 pandemic, much still remains unknown about the transmission of respiratory viral infections, and how NPIs should best be used to mitigate infection risk. In this section, we briefly highlight some of the major knowledge gaps that exist.

319. Although the aerosol route (be it near-field or far-field) is now recognised as a major pathway for SARS-CoV-2 transmission, we do not know to what extent other routes (i.e., large droplets, hand contact, contaminated fomites, etc.) contribute to the burden of Covid-19 in the NHS.

320. Similarly, we do not know the relative contributions made by near-field and far-field aerosol transmission to the burden of Covid-19 in the NHS.

321. Although the physical science underpinning potential aerosol transmission of influenza and RSV is exactly the same as that for SARS-CoV-2, both these infections remain classified as droplet-borne (NHS-England 2022). While this appears an obvious inconsistency, and there is good reason to believe that these infections might be transmitted by similar routes to Covid-19, we don't know the extent to which this is the case.

322. Much remains unknown about the ventilation rates required in hospital wards, staff rooms, and non-clinical spaces to effectively mitigate the risk of airborne infection. The HTM guidelines (NHS-England 2021a) specify ventilation rates for general wards and ancillary spaces that are based on odour control, comfort and energy criteria, rather for infection control purposes. With respect to this, CO_2 monitoring appears to have some potential as a tool for assessing, and specifying required, ventilation rates. However, little is known about how CO_2 monitoring should be used in hospitals to improve patients and HCW safety.

323. Similarly, very little is known about movement of air and aerosols within and between hospital wards. In particular, little is known about the best ventilation strategy to prevent regions of high aerosol concentration occurring.

324. With respect to portable air cleaners, while these can be used to boost effective air change rates, very little is known about how and where these should be deployed to best effect. Furthermore, there is a lack of high-quality epidemiological evidence, with infection outcomes rather than proxy outcomes, to inform how they should be used in healthcare facilities.

325. Similarly, while upper-room UV and far-UVC look very promising, these technologies have not been trialled in UK hospitals, and therefore more evidence is required to determine their suitability for use in the NHS.

326. Much remains unknown about how facemasks should be deployed in the NHS to best effect. Currently, emphasis is placed on the general use of surgical masks to reduce the exhalation of infectious droplets and larger aerosol particles into the air, with very little regard to the inhalation of fine aerosols that pass through gaps between the mask and the face, and which are more likely to contain virus (Alsved et al. 2023a; Coleman & Sigler 2020; Coleman et al. 2022; Jaumdally et al. 2024; Yan et al. 2018). However, relatively little is known about the effectiveness of this strategy, and whether it could be improved. Improvements could also be made to the design of facemasks to reduce the inhalation of respiratory aerosols, while still maintaining utility, resulting in superior performance over surgical masks. With respect to this, **the use of FFP2 masks with ear loops should be investigated as an alternative to surgical masks. Although these do not provide the same level of protection as FFP3 respirators with head straps, they are much more comfortable and there is good evidence that they provide superior protection against infectious aerosols compared with surgical masks** (Bagheri et al. 2021).

Lessons learnt from the Covid-19 pandemic

327. In this section we consider some of the broad-brush lessons to be learnt from the Covid-19 pandemic. Rather than concentrating on particular NPIs or the physical science associated with the transmission of respiratory infection, we instead focus here on some of the over-arching themes that came out of the pandemic.

328. Over many years, thinking amongst many medical and IPC professionals has been shaped by a number of *a priori* assumptions (e.g., respiratory viruses are not airborne, particles >5μm cannot travel further than 2 meters, etc.), which whether true or false, have become 'baked' into the scientific literature and have shaped much IPC policy on the transmission of respiratory viruses. These ideas have proven very resistant to change, despite the evidence underpinning them often being surprisingly weak, and some of the assumptions being incorrect. Furthermore, over time a silo mentality developed, that became dismissive of ideas form other disciplines, as evidenced by the reluctance of the WHO to consider that SARS-CoV-2 that might be transmitted by the airborne route (Lewis 2022; Morawska et al. 2023). Indeed, it was only when a more multidisciplinary approach was taken that challenged some of the *a priori* IPC assumptions, that a better understanding of the transmission of SARS-CoV-2 emerged. Therefore, the take-home message here is: ***When evaluating the evidence regarding the transmission of disease and the use of NPIs it is important to take a multidisciplinary approach which considers the physical science as well as the epidemiological evidence.***

329. Historically, when reviewing evidence, there has been a tendency to place great emphasis on randomised controlled trials (RCTs) and the GRADE assessment system, with evidence obtained from observational and modelling studies often downplayed or ignored. However, RCTs investigating transmission and the efficacy of NPIs are very difficult to undertake, and are often compromised by operational and clinical factors that make such studies difficult to control.

Consequently, in many areas, few RCTs exist, and the evidence when it does exist it is often inconclusive and low-quality, as highlighted by the Royal Society working group investigating the impact of NPIs during the Covid-19 pandemic (Walport & RS Working Group 2023). However, when modelling and other physical science evidence is considered, it is often possible to gain deeper insights and draw firmer conclusions (Walport & RS Working Group 2023). Therefore, the take-home message here is: ***When evaluating the evidence regarding the transmission of disease and the use of NPIs, as well as considering the evidence from RCTs, it is important to carefully considered evidence acquired from observational, laboratory and modelling studies.***

330. From the historical literature, it is clear that the *a priori* assumption that the vast majority of the viral load was likely to be in larger respiratory droplets meant that evidence from animal and outbreak studies was interpreted as supporting droplet transmission, rather than aerosol transmission (PIP-Team 2011b). This led to a blind spot, which ultimately meant that:

    i) The NHS was not adequately prepared for a pandemic of airborne viral disease.

    ii) The NHS (along with the WHO and CDC) did not recognise that Covid-19 was an airborne disease when it arrived, and were reluctant to accept new evidence that the disease could be airborne.

    iii) The NHS did not have the necessary ventilation infrastructure in place to adequately mitigate transmission of SARS-CoV-2 on general and acute wards.

331. Therefore, the take-home message here is: ***Because of an a priori assumption about the distribution of viral load in exhaled respiratory droplets there was a blind spot, which meant that it was assumed that the next pandemic would be droplet-borne, rather than airborne. This ultimately meant that the NHS was not adequately prepared for a pandemic of airborne disease.***

332. **Scientific evidence acquired during the Covid-19 pandemic has shown that the old classification system of 'airborne' or 'not airborne' used in the NHS HTM ventilation guidelines** (NHS-England 2021a; NHS-England 2021b) **is no longer fit for purpose, and is in urgent need of revision.**

Recommendations:

i. A more multidisciplinary approach should be taken to future pandemic preparedness by the UK Government, including but not limited to hospital IPC. This should specifically include scientific advice from experts in the physical sciences, similar to the SAGE Environmental Modelling Group, but also working on pandemic preparedness as well as emergency response.

ii. Prevention and control of respiratory infections before and during the next pandemic would be assisted by further multidisciplinary research to better understand transmission of Covid-19, influenza, and other pathogens so that the contribution of each potential transmission route can be quantified and its relative importance assessed. In particular, it is important to understand the relative proportion of infections that are transmitted in the near-field as opposed to the far-field so that effective strategies can be developed to mitigate transmission via exhaled respiratory particles.

iii. Much confusion currently exists in the terminology used in healthcare system guidance from across the UK concerning the transmission of infection through the air, with ambiguous terms used and statements made that are often at variance with the physical science. Although the WHO is currently attempting to rectify this situation, there is nonetheless an urgent need to remove ambiguity from the IPC and HTM guidelines and ensure that these are consistent with the state-of-the-art physical science associated with the transmission of disease. In particular, the "droplet route" of transmission, as currently defined, is ambiguous and has no basis in physical science.

iv. Although infectious aerosols produced by AGPs pose a threat to HCWs, for many AGPs the risk appears to be less than that associated with the natural aerosols exhaled by Covid-19 patients when breathing, speaking or coughing. Yet the IPC guidance for healthcare in the UK devotes much more attention to the former compared with the latter, despite the fact that over the many hours that an infectious person is present, these everyday activities liberate many, many more respiratory aerosols into the air compared with AGPs. Whether or not AGPs are being conducted in a space is not the only or even the most important determinant of airborne infection risk. It is therefore recommended that consistent IPC guidance be developed to mitigate the risk posed by infectious aerosols, be they generated by AGPs or naturally exhaled by SARS-CoV-2 and influenza patients. In particular, the duration of time that someone is exposed is of critical importance and should be acknowledged in guidance.

v. Multiple lines of epidemiological and physical science evidence now suggest that FFP3 respirators provide better protection for HCWs caring for patients with SARS-CoV-2 than surgical masks. This raises questions about whether loose fitting surgical masks (FRSMs) provide adequate protection to HCWs when caring for Covid-19 patients. Therefore, barriers in the way of wider respirator use, whether due to guidance, regulation, fit testing, supply or comfort should be addressed urgently by the UK Government to ensure that more effective respiratory PPE is widely available before and during the next pandemic and that HCWs are better protected during their routine activities. In particular, consideration should be given to alternative facemask solutions, such as FFP2 masks with ear loops, which offer superior protection against the inhalation of infectious aerosols compared with surgical masks, while being more comfortable than FFP3 respirators with head straps and not requiring a fit test.

vi. There is a need for further multidisciplinary research to better understand how air and infectious aerosols move around hospital wards, so that appropriate strategies and standards can be developed for hospital ventilation systems to mitigate the transmission of infection.

vii. There is a need for robust evidence and guidelines on the deployment of portable supplementary air cleaning devices (both HEPA and UVC devices) in hospitals, before and during the next pandemic. The evidence base in support of portable HEPA devices, in particular, is reasonably strong, since these perform a similar task to mechanical ventilation systems, and as such are a mature well-established technology that is quick and relatively inexpensive to deploy. To support this, there is a need to better understand where and how these devices should be deployed to best effect to mitigate the transmission of infectious disease.

viii. Although fixed installation UV systems appear to have considerable potential to reduce viable viral loads in room air, their real-world effectiveness, including in healthcare settings, is largely un-tested. Consequently, there is a need for further funded research into the safety and implementation in healthcare settings of upper-room UV and far-UVC air disinfection technologies as part of a suite of pandemic preparedness research. A sufficient evidence base is required to support their widespread adoption.

ix. There is an urgent need to revise and upgrade the NHS HTM guidelines on hospital ventilation so that they reflect the state-of-the-art science regarding the transmission of respiratory viruses in the post-Covid era. In particular, these guidelines need to consider the risks posed by patients and HCWs with regard to Covid-19 and influenza on general wards and in non-clinical areas such as waiting and staff rooms, so that prescribed ventilation regimes fulfil their role in the hierarchy of IPC controls and ensure that viral loads in the room air are maintained at safe levels. These guidelines will also need to be updated with regard to other pathogens, particularly newly emerging pathogens, as evidence emerges. With respect to this, the HTM documents need to give practical guidance regarding the use of supplementary air cleaning devices, so that they can be deployed to best effect to mitigate the transmission of disease. They also need to consider the role that CO_2 monitoring might play in ensuring that day-to-day ventilation rates in clinical and non-clinical spaces are maintained at appropriate levels.

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