This is the accepted version of the publication Tsang TW, Wong LT, Mui KW. Experimental studies on airborne transmission in hospitals: A systematic review. Indoor and Built Environment. 2024;33(4):608-640. Copyright © 2023 The Author(s). DOI: 10.1177/1420326X231205527.

Experimental studies on airborne transmission in hospitals: A systematic review

Keywords

Experimental sciences, airborne transmission, airborne infection, hospital, ventilation, environmental factors

Abstract

Experimental studies can provide understanding, knowledge and real-case empirical evidence on the effects of building ventilation and environmental factors on airborne transmission in hospitals. Information obtained from existing studies gives insight into formulating engineering solutions and management practices to combat nosocomial airborne infections. A systemic review was conducted to summarize the experimental methods, research interests, useful results and limitations. With a steady but slow trend of increasing interest, experimental studies have been focusing mainly on the effects of ventilation systems, strategies and configurations on airborne transmission. The dispersion of bioaerosols under the combined effects of environmental factors, emission scenarios and human movement was investigated. Localized ventilation, air purifiers and disinfection technologies were also examined. The experimental techniques and some useful insights on optimal ventilation strategies and management practices were summarized and highlighted. Limitations of the empirical studies included sampling difficulties, limited scale and a number of testing scenarios, uncontrolled/ unconsidered influencing factors and the media for experimentations. Using IoT-based sampling devices for experiments and real-time monitoring of bioaerosols or their surrogates, field surveys on a case-by-case basis in hospitals and interdisciplinary studies and collaborations could help overcome the research challenges and provide practical and effective solutions to minimize airborne transmission in hospitals.

Introduction

Coronavirus Disease 2019 (COVID-19) pandemic has reshaped the world of academic research by redirecting research resources into studying COVID-19.[1] Despite the denial of COVID-19 being airborne by the World Health Organization (WHO) during the first two years of the pandemic,[2] more and more empirical evidence has been unearthed through field measurements of the presence of SARS-CoV-2 RNA in the air samples, with some even discovered the viable and infectious virus in the sampled aerosols, e.g., Vass et al.[3] and Lednicky et al.[4]. Long-range transmissions were observed in some indoor environments such as restaurants, public transportation and hospital wards,[5–9] together with some cases of horizontal and vertical transmissions through natural ventilation and stack effects in residential buildings, this epidemiological evidence suggested a high possibility of airborne transmission induced by airflow.[10,11] Bibliometric analysis of COVID-19-related research revealed "risk of transmission and infection in healthcare workers" as one of the research niches aroused during COVID-19.[12] The findings have encouraged the development of engineering research into the effects of building environment and ventilation on airborne transmission at an unprecedented speed.

The association between building ventilation, air movement and airborne infection transmission has long been proven with sufficient and compelling evidence. Yet, a joint agreement on the quantity of ventilation required to minimize airborne infection risk still needs to be developed.[13] Understanding the effects of environmental and human factors on airflow and the transport of bioaerosols is particularly important in hospital environments due to the high rate of occurrence of airborne diseases, known or novel, and crowded spaces filled with healthcare workers, visitors and vulnerable patients. Notably, environmental factors such as room layouts, bed arrangements and indoor environmental quality (IEQ) factors, including temperature and humidity, as well as human factors such as the movement of people, door opening motions and infected patients' exhalation modes, can significantly influence the aerosol transmission of infectious agents.[115] These factors should be considered when evaluating the risk of airborne transmission in indoor environments and developing effective control strategies to mitigate the spread of airborne pathogens. Preventing nosocomial airborne transmission through engineering controls and management practice, especially in general hospital patient areas, could be the cornerstone to avoiding the next pandemic.[14] Therefore, current research in the field provides a scientific foundation and supports establishing policies and guidelines for mitigating airborne infection risk through building ventilation and management controls.

There are two major approaches to studying airborne transmissions in indoor environments under the influence of building ventilation and environmental factors: theoretical mathematical models and experimental studies. A theoretical approach such as numerical models could provide exceptionally precise and comprehensive understandings of the aerodynamics of airborne pathogens and simulate their movement in the air, however, based on a series of laws of physics and ideal assumptions. On the other hand, experimental studies, although often limited to some case scenarios, offer accurate and real-case empirical evidence, knowledge and information built from observation for engineering interpretation.[15] Despite numerical models' ability to obtain information unavailable through experimental studies or quickly at a reduced cost, accessing the accuracy of the theoretical models through validating the computation with experimental data is crucial to avoid inaccurate and misleading results.[16] Empirical studies, therefore, have not only the merit of providing physical evidence to support engineering decisions but also the complement to theoretical studies.

To provide a thorough understanding of experimental research and summarize physical experimental evidence on the effects of building ventilation and environmental factors on airborne infection transmission in hospital environments, this study reviewed through a systemic process on the literature in the long-standing field of experimental studies of airborne transmission concerned, including the research methodologies adopted, the research interests and limitations. The conclusions or suggestions supported by empirical evidence provided in the studies were summarized. The research challenges and constraints in the field and the potential future research directions were also discussed.

Methods

Applicability of the study findings

A general hospital is a healthcare facility that provides a wide range of medical services, including patient care areas for operations, emergency treatment and patients. It also houses functional rooms such as radiology, laboratory, along with ancillary support services such as a kitchen, dining and food service, and morgue. However, caution must be taken when applying the appropriate ventilation strategies to prevent airborne transmission within hospitals compared to other healthcare facilities such as nursing and dental facilities. This is because specific criteria with respect to various medical procedures are required to ensure the health and safety of patients, healthcare workers and visitors. In general, ventilation requirements in hospitals include:[17]

1. Restrictions on air movement between departments;
2. Specific ventilation and filtration requirements to remove contamination;
3. Different temperature and humidity requirements for various areas; and
4. The need for sophisticated design for accurate environmental control.

While this review centres on experimental studies on the impact of building ventilation and environmental factors on the dispersion of airborne pathogens in hospitals, the research findings, including the experimental methods, challenges and limitations, are broadly applicable to other indoor environments. However, modifications to the study design and experimental methodology are necessary to meet the specific requirements of the indoor environment and research objectives.

Research questions

Experimental studies provide crucial empirical evidence on the effects of building ventilation and environmental factors on the dispersion of airborne pathogens in hospital environments. This review discussed the experimental methods, research interests and limitations of existing studies in the field and provided future research directions. The research questions for this review are listed below:

1. What is the research trend in airborne transmission experimental studies in hospital environments?
2. What were the research interests and results of the existing studies?
3. What experimental methods were adopted and why?
4. What were the research challenges and limitations?
5. What will be the future research directions for the field?

Search strategies

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) published in 2020.[18] Figure 1 shows the PRISMA flow diagram for systematic reviews. Articles were searched using Clarivate's Web of Science with the keywords and search formula "transmission (All Fields) AND ventilation (All Fields) AND hospital (All Fields) AND experiment (All Fields)". A total of 96 records from 1986 to March 2023 resulted. Since this review focused on the experimental evidence rather than the theoretical knowledge of the effects of ventilation on airborne transmission in hospitals, to narrow down the research results, studies that involved computational fluid dynamics (or CFD), a standard theoretical method to study the airflow and evaluate the transportation of airborne pathogens or particles, were filtered out using the search formula "NOT computational fluid dynamics OR CFD (All Fields)", resulting in 80 publications.

Similarly, the keywords were searched using Scopus and PubMed, resulting in 1,811 and 36 journal and conference articles. The author(s), titles, abstracts, document types and keywords were exported from the search engine for further screening to remove irrelevant studies. The selection criteria of these studies were as follows:

Include: -

1. Research study must be conducted based on experimental sciences;
2. The study must be concerned with airborne transmission and ventilation;
3. The study must be conducted in hospital environments (or mock-up); and
4. The research paper must be written in English.

Exclude: -

1. Duplicate publications, such as having the same study published as both conference and journal articles;
2. Secondary studies such as reviews;
3. Studies that did not concern the building ventilation or other environmental factors; and
4. Studies with limited experimental data were collected to validate simulation models.

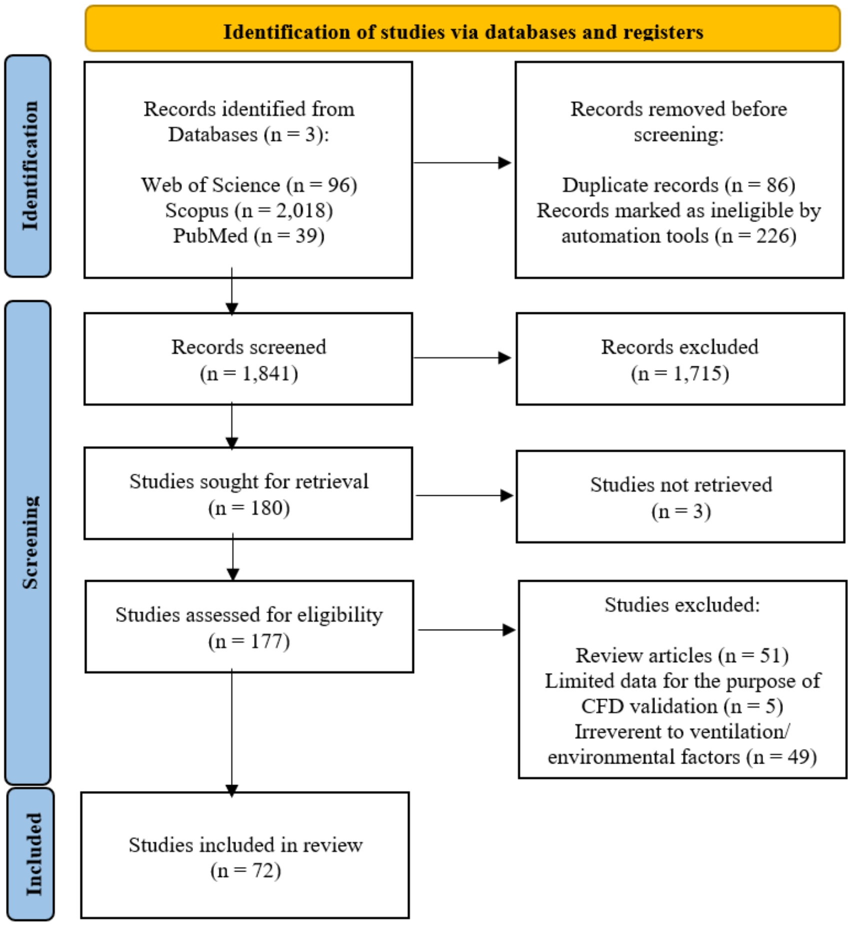


Figure 1. PRISMA flow diagram for systematic reviews.[18]

Results and Discussion

Systematic review

Table S1 in the supplemental material exhibited the systematic reviews concerning building ventilation, risk factors, airborne transmission and mitigation strategies in indoor environments. Several review articles were retrieved from the database during the screening process, and the objectives, research questions and results were examined. These studies were not considered in the review process, but the information retrieved helped identify the research aims of this study. The review articles were classified into one or more categories according to the research areas reviewed. Majority of the reviews aimed at summarizing the prevention practices, mitigation strategies and design practices in reducing airborne transmission or transmission of diseases in general. Some reviewed current understandings of the role of ventilation or ventilation systems on airborne transmission and infection and identified optimal ventilation practices to minimize the risk. Due to the severity of the COVID-19 pandemic, a few reviews were devoted to summarizing the environmental evidence of SARS-CoV-2 being airborne and transmissible through aerosols in recent three years. Based on the literature search, no systematic review discussed the field's experimental studies. As such, this study provided a comprehensive review of the research methodologies, interests, aspects of airborne transmission concerned, results and evidence, research challenges and limitations of the experimental studies on the effects of building ventilation and environmental factors on the transmission of airborne infection in hospital environments. The potential future research directions were also highlighted.

Research trend

A total of 72 journal and conference articles were included in this review. The annual publication records of the experimental studies on the effects of ventilation and environmental factors on airborne transmission in hospitals are presented in Figure 2. The earliest studies are dated back to 1995, which discussed the usage of portable filtration units for reducing aerosolized tuberculosis-containing aerosols. Hardly any studies were conducted in the subsequent years. Most studies were born in the recent five years, especially in 2022, due to the acknowledgement and raising of concerns regarding the nosocomial transmission of airborne infection of SARS-CoV-2. Overall, the steady growth of experimental research in this field can be observed. Yet, the number still needs to be increased to provide adequate physical evidence for addressing the research issue.

From Figure 2, the research interest trend varied over 28 years. Increasing interest in the effects of ventilation systems, strategies and configurations on airborne transmission was observed, contributing to about 60% of the studies reviewed. Some research efforts were put into understanding the dispersion of airborne pathogens affected by environmental conditions, ventilation and human movement. Air disinfection has become popular since 2022, attributed to the COVID-19 pandemic, during which researchers were desperate to identify mitigation strategies to minimize airborne transmission in hospitals.

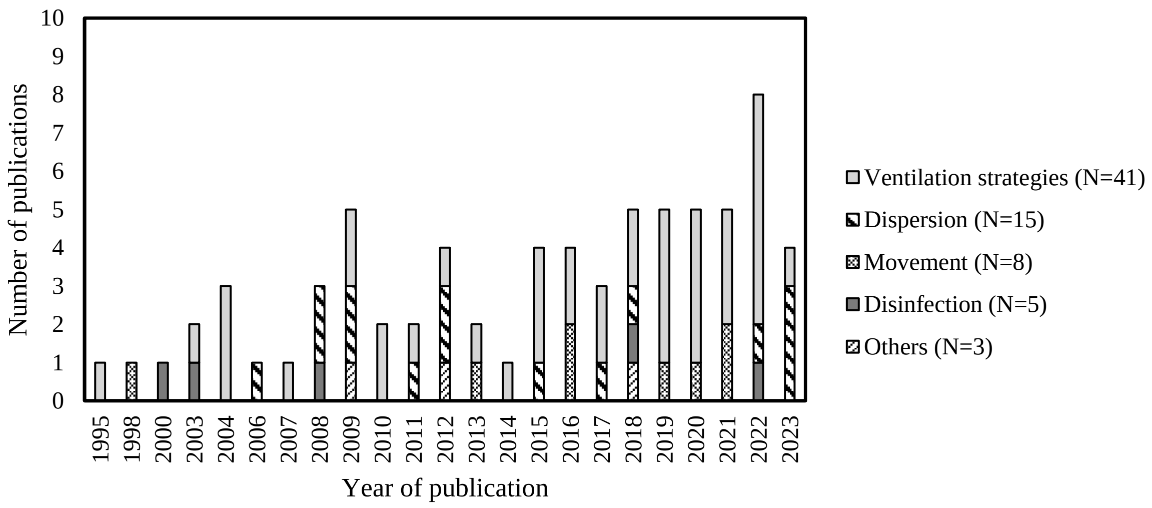


Figure 2. Number of publications from 1995 to March 2023 under various research interest categories.

Keywords co-occurrence

Keywords co-occurrence network examines the linkages between keywords and facilitates our understanding of the field's knowledge components and structure through visualization.[61] Identifying the keywords with high co-occurrence frequency also allows the discovery of the main topic of interest and provides insight into future research direction. The VOSviewer was adopted to create the keywords co-occurrence network using author keywords. Since having a long list of co-authors in a publication in this field is common, fractional counting was employed to ensure each study has the exact weighting as the others. Out of 72 articles reviewed, 187 keywords resulted. For each of the 40 keywords with a minimum number of two keyword occurrences, the overall strength of co-occurrence links with other keywords was calculated and presented in Figure 3. Table 1 exhibits the top three keywords under each attribute. Analysis results suggested that “airborne transmission”, “infection control” and “ventilation” are three main keywords in the field. In particular, “infection control” was linked not only to the other two main keywords but also several keywords related to building ventilation, for example, “positive/ negative pressure”, “downward ventilation”, “air distribution”, etc. Several high-frequency keywords indicated some core research locations and research methods adopted in existing studies, such as the keywords “operating room/ theatre”, “hospital ward/ room”, “isolation room”, “full-scaled experiment”, “flow visualization” and “tracer gas”.

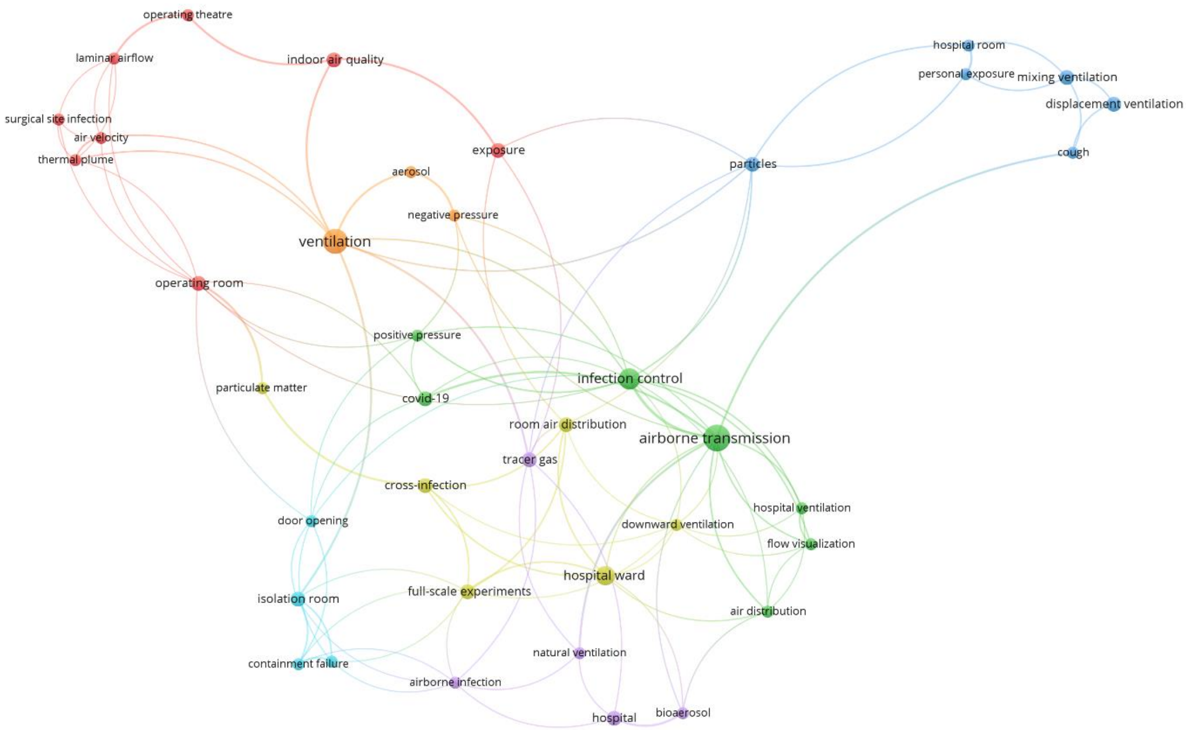


Figure 3. Author keywords co-occurrence network visualization weighted by occurrences created using VOSviewer.

Table 1
Top three keywords under each keywords co-occurrence attribute

Links	Total link strength	Occurrences	Average citations	Average normalized citation
airborne transmission (12)	airborne transmission (8)	airborne transmission (9)	flow visualization (167)	particulate matter (2.4)
infection control (12)	infection control (6)	ventilation (8)	hospital ventilation (167)	cross-infection (2.0)
operating room (9)	ventilation (6)	infection control (6)	air distribution (118)	bioaerosol (1.7)

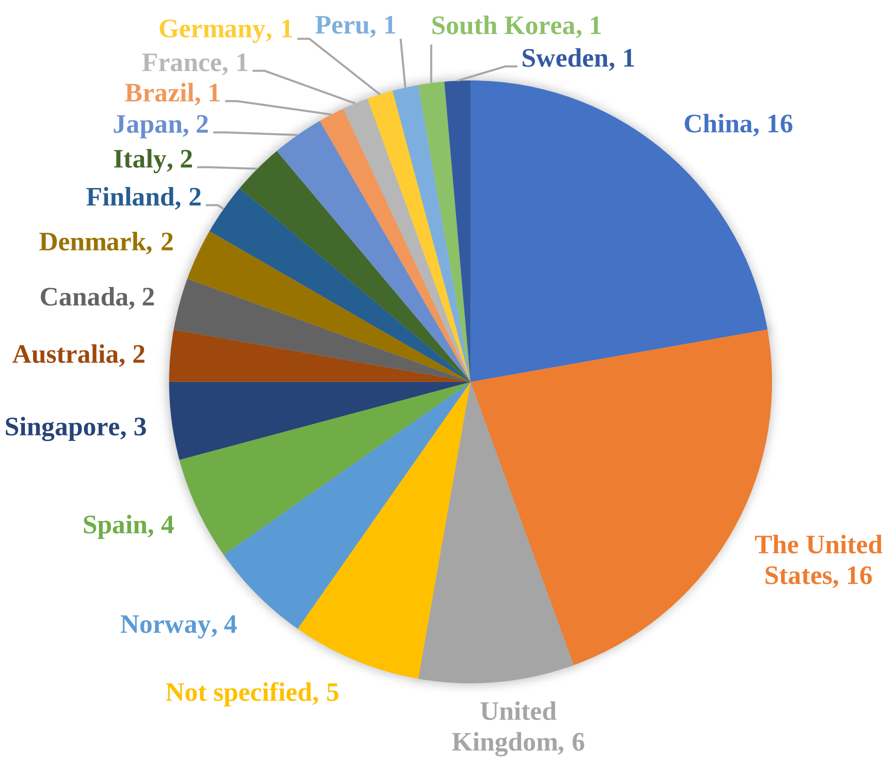
Footnote: The number in the brackets under links and total link strength represents the number of connections of each keyword. The number in the brackets under occurrences indicates the number of times the keyword appears in the studies reviewed. The number in the brackets under average citations and average normalized citations suggests the average and normalized number of citations of the studies that contain this keyword.

Research interests

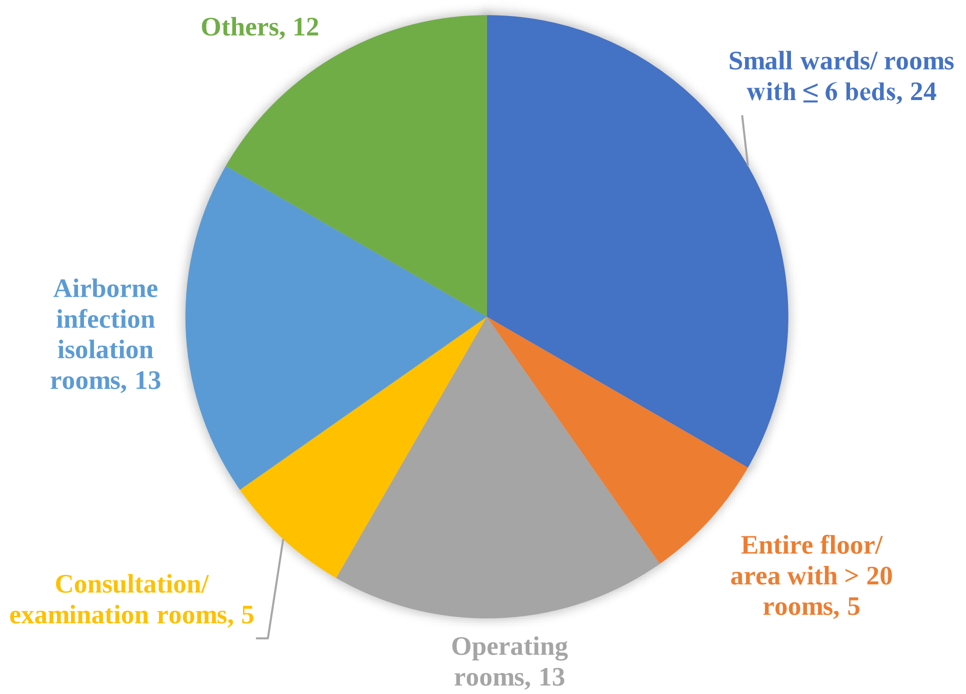
Geographical distribution and study locations

The majority of studies on airborne transmission in hospitals have been conducted in China and the United States, with several others spread across Europe and some Asian countries. Notably, eight articles were conducted by research teams from Hong Kong, making it the most represented location amongst different experimental studies. These studies were conducted primarily between 2006 and 2010, possibly due to an increase in research interest following the 2003 SARS outbreak in Hong Kong. Taiwan also contributed significantly to identifying the effectiveness of ventilation and disinfection technologies in minimizing airborne transmission and cross-infection in hospitals.

One-third of studies focused on small wards or patient rooms with six beds or fewer. Equal attention was given to rooms with special functions, such as operating rooms for surgical purposes and airborne infection isolation rooms (AIIR) designed to prevent the spread of droplet nuclei expelled by patients infected with airborne diseases. Efforts were made to understand and minimize airborne infection risks in consultation or medical examination rooms. In contrast, others evaluated the dispersion of airborne pathogens throughout entire floors or general wards with more than 20 patient rooms. The remaining studies were conducted in less-discussed areas, such as bathrooms, intensive care units (ICU), laboratories and administrative offices. Figure 4 displays the distribution of reviewed studies based on their geographic locations and their respective study locations within hospitals.



(a)



(b)

Figure 4. (a) Geographical distribution; and (b) study locations of the publications reviewed.

Ventilation strategies/ configurations

Forty-one studies investigated the influence of ventilation strategies or configurations on airborne transmission. Amongst them, 17 explored the use of alternative ventilation systems or modes (e.g., mixing ventilation, displacement ventilation, natural ventilation, etc.),[62–67] configurations (e.g., air change rates, pressure differentials, exhaust-return locations, etc.),[68–75] system operational controls[76,77] and system filtering units[78] in reducing the exposure to airborne particles and contaminants and the infection risk of airborne diseases. Five identified the exposure and risk of cross-infection under various ventilation configurations.[79–83]

Relatively massive efforts have been put into identifying the optimal ventilation strategies and configurations for infection control in hospitals. However, some conflicting conclusions were identified, especially on the air change rate (ACH). For instance, the conventional belief of a high ACH for lower infection risks was questioned by experimental studies that found the effectiveness of ACH depends on the mode of ventilation, the degree of air mixing and environmental conditions.[63,71,79] One study suggested that an increase in ACH for contaminant removal was less effective than containing the movement of aerosols through directional airflow.[69] Mixing ventilation with ACH of $12h^{-1}$ suggested by hospital guidelines failed to eradicate the risk of airborne infection.[73] Alternatively, a few studies indicated that the relative position of the ventilation supply and exhaust, the infected patient and the susceptible, and the posture of the patient when the bioaerosols were emitted significantly determined the spatial distribution of the contaminants and the level of exposure.[66,71–73,82]

Under this category, 11 studies investigated the use of personal or localized ventilation units[84–94]. The remaining 8 discussed the use of air purifiers and air cleaners with high-efficiency particulate air (HEPA) filter[95–102] to minimize exposure to infectious aerosols. These experimental studies showed that add-on portable ventilation devices could effectively contain and remove aerosolized particles. The position of the apparatus relative to the source patient and the susceptible will require further research to optimize the efficacy and minimize discomfort.[88,91,99]

Dispersion

Understanding the dispersion of aerosols under the influence of ventilation is crucial to some epidemiology studies. The experimental results could be the empirical evidence for identifying the transmission pathways and verifying the infection timeline. Sung et al.[103] confirmed experimentally that indoor airflow made the long-distance spread of the Middle East Respiratory Syndrome (MERS) infection possible. The tracer gas's bioaerosols surrogate dispersion pattern matched perfectly with the epidemiologic observations, indicating the infection routes via ventilation in the hospital. Similarly, the dispersion of DNA-barcoded aerosols was tracked to examine the transmission pathway of a cluster of SARS-CoV-2 infections amongst hospital staff.[104] The unique aerosols were found widely dispersed throughout the floor, potentially facilitated by ventilation air movement or recirculated air without adequate filtering, demonstrating the possibility of airborne infections amongst the cluster. Huang et al.[105] also used tracer gas to investigate the spatial relations and potential airborne transmission within nosocomial COVID-19 groups.

One study aimed at identifying the aerodynamic behaviours and the dispersion patterns of aerosol particles and tracer gas,[106] and another investigated the feasibility of estimating the exposures to airborne viruses using the spatial distribution of expiratory aerosols and the viability functions of airborne viruses.[107] Other studies in this category evaluated the combined effects of ventilation configurations, layouts, locations of the infected patient and the susceptible, source patient's postures, exhalation modes and source of bioaerosols on the aerodynamics and the dispersion pattern of bioaerosols.[108–117]

Effects of human movement

A handful of studies investigated human movement's effects on airflow and aerosols' dispersion. These studies mainly concerned two kinds of human activities: door opening and passage through the doorway. The influences of door types, speeds and durations of a door opening, speeds and directions of human passage, and ventilation conditions on air volume exchange and migration were examined. Study results showed a more significant effect on airflow and air volume exchange across the hallway with a hinged door than the sliding door. The effect of passage through the doorway was also notable and more prominent for the sliding door case.[118–120] A long door opening time could cause an almost complete air volume exchange between two rooms.[121] Opening the door repeatedly also induced a greater magnitude change in airflow velocity as the latter door movement interacted with the flow field exerted by the first.[122] While door opening is unavoidable during daily hospital practice, the effects of door movement and passage on airflow can be counteracted by engineering solutions. Kalliomäki et al.[123] recommended using directional airflows to limit the undesired air escape induced by the door opening, passage and temperature difference.

The remaining two studies explored the effects of movement on airborne bacterial distribution in the operating theatre. A study found that unwanted disturbance factors such as unnecessary door openings, personnel, movement and talking could cause high microbial and particle contamination.[124] Higher levels of activity around the surgical bed caused higher bacterial contamination. Places with obstructions had the highest level of bacteria in the air, indicating the importance of airflow patterns and ventilation in infection control.[125]

Disinfection

Few studies evaluated the effectiveness of air disinfection technologies in reducing exposure to pathogenic aerosols. Most discussed the application of ultraviolet germicidal irradiation (UVGI) in hospital environments to inactivate microorganisms in the air. UVGI technologies can be applied in the ducts of the fan coil of the HVAC system,[126] at the upper part of the room (upper-room UVGI)[127–129] or as portable devices.[126] Experimental results generally showed a promising disinfection efficacy with UVGI. The effectiveness depended on environmental conditions, the number of UV fixtures, ventilation rates and target microorganisms.[127–129] Besides using UVGI, other technologies for disinfection in hospitals, such as titanium (IV) oxide (TiO_2) were tested.[130]

Evaluation indices for risk of airborne infection

Some studies further analyzed the experimental results to establish the infection risks of the case scenarios. There are a few recognized and commonly used evaluation indices for estimating the risk of airborne infection. The most notable one used in the studies is the intake fraction.[131] Shown in Equation (1), the intake fraction (iF) quantifies the emission-to-intake relationship, which is described as the proportion of aerosols inhaled by the susceptible to those emitted from the infected patient, where C_i and C_h are the mass of aerosols inhaled by the susceptible and exhaled by the infected patient.

$$intake\ fraction\ (iF) = \frac{C_i}{C_h} \qquad (1)$$

Another index commonly used is the personal exposure index ε_e, which is used as an indicator of exposure level to infectious microbes in the air, is defined in Equation (2), where C_R, C_S and C_e are the average concentrations at the ventilation return, supply and the inhaled air of the susceptible.[132]

$$personal\ exposure\ index\ (\varepsilon_e) = \frac{C_R - C_S}{C_e - C_S} \qquad (2)$$

With the information on the ACH of an environment, infection risks can be estimated using the Wells-Riley airborne infection model. Developed by Riley et al.[133], this model estimates the probability of infection (P_i) by inhaling one quantum of infectious disease in the air after spending a certain amount of time in the room with the infected patient. Equation (3) shows the derived Wells-Riley equation with C being the number of infection cases, S and I the number of susceptibles and infectors, p the pulmonary ventilation rate of a person, q the quanta generation rate estimated from outbreak cases through epidemiological studies, t the exposure time and Q the room ventilation rate.

$$Probability\ of\ infection\ (P_i) = \frac{C}{S} = 1 - e^{-\frac{Iqpt}{Q}} \qquad (3)$$

The above-mentioned evaluation methods for airborne infection risk assessment are simplified ways to describe the physical transportation of airborne pathogens from the infected patients to the susceptibles. When the infection is concerned (i.e., whether the susceptibles are infected after being exposed to the infectious aerosols), the dose-response model, which interprets the dose-response relationship of a particular virus or bacteria based on infectious dose data obtained from experimental or empirical studies, is required.[134]

Experimental methods

Airborne pathogens are released to the surroundings through respiratory processes like breathing and coughing. Depending on the exhalation mode, the exhaled droplet nuclei sizes differ.[135] Due to the effect of gravity, larger droplets are deposited on the wall, the floor or any surfaces soon following exhalation, or else they will evaporate, decrease in size or follow those droplets in a size range of 0.8–3 μm to suspend in the air and transport along with the airflow.[136] Bivolarova et al.[106] compared the distribution patterns of tracer gas (nitrous oxide, N_2O) and aerosol particles (size of 0.7 μm) under various ventilation rates in a single-bed hospital room. They found that for a person in a supine position under the influences of free convection flow and ventilation airflow, the dispersion of the small-sized particles was the same as that of the tracer gas. To simulate the movement of infectious aerosols over a significant distance from the source, tracer gases or smaller-sized aerosols are usually preferred as they are not influenced by buoyancy.

Based on the review, more than one experimental technique was generally employed in the experimental studies. Both tracer gas and aerosols were commonly used techniques to simulate the movement of bioaerosols. Smoke was sometimes used for visualizing the airflow pattern and direction. Experimental studies were often conducted in full-scale mock-up wards or real hospitals to investigate the dispersion of airborne pathogens under the influence of ventilation and environmental conditions.

<u>Tracer gas experiment</u>

The use of tracer gas as a surrogate for bioaerosols in experimental studies involves injecting a known amount of gas into the air and tracking its movement and concentration. This technique has been widely employed in empirical studies conducted in real hospitals or simulated hospital environments to identify airflow and airborne transmission pathways. The technique can be easily implemented in large areas in real hospitals with minimal disturbance to regular operation, making it ideal for outbreak investigation (e.g., Sung et al.[103] and Huang et al.[105]). This technique was also used in mock-ups to investigate respiratory contaminants' dispersion influenced by various factors, including building ventilation. The experimental set-up constructed by Qian et al.[111] for identifying the exhaled bio-contaminant dispersion under different exhalation modes, face orientations and ventilation strategies using N_2O released from a manikin is shown in Figure 5 to demonstrate the tracer gas technique.

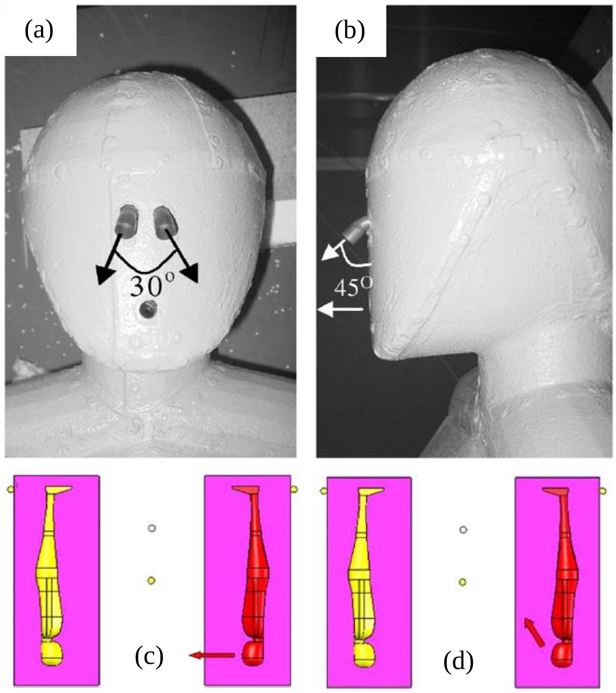


Figure 5. (a) and (b) Photos of the manikin employed to simulate the exhalation of biological contaminants using tracer gas N_2O under different exhalation modes and face orientations; (c) the direction of the exhalation jet during mouth-breathing; and (d) the direction of the exhalation jet during nose-breathing.[111]

Tracer gases such as sulphur hexafluoride (SF_6) and nitrous oxide (N_2O) are commonly used in experimental studies due to their favourable properties, including non-toxicity, low atmospheric concentration and detectability at low concentrations. The widely used tracer gases and their properties are listed in Table 2.

The use of tracer gas as a surrogate for bioaerosols in experimental studies has been questioned due to the physical dissimilarities between expiratory droplets and tracer gas molecules. However, several studies have examined their movements under the influence of building ventilation and found that tracer gas behaved similarly to small aerosols.[63,106] It is preferred by many due to its relative simplicity and ease of use, making it a more accessible option for researchers with varying levels of expertise.[137]

Nonetheless, it is important to carefully consider whether using tracer gases as surrogates is appropriate for a given research project, considering the specific goals and experimental conditions. Although the spatial and temporal tracer gas concentration can indicate the potential spread of infection, it is important to note that the tracer gas concentration is not equivalent to the infection risk. A linkage, i.e., an airborne transmission model like the Wells-Riley model, is needed to identify the risk of infection. The viability and infectivity of bioaerosols are also not reflected by tracer gases which environmental factors can influence. Besides, due to the natural difference, tracer gases cannot adequately represent the deposition and resuspension of bioaerosols on surfaces.[137] Despite the inadequacy, the tracer gas technique gives a quick and repeatable experimental method for determining airflow. Therefore, it has been recognized and supported as an effective and suitable surrogate for studying airborne transmission in the built environment.

Table 2

Common tracer gases for identification of the airflow and airborne transmission pathways

IUPAC name (Chemical formula)	Molar mass (g/mol)	Density (kg/m^3)	Ideal properties for airborne transmission studies
Sulphur hexafluoride (SF_6)	146.06	6.17	- Low toxicity - Does not exist in typical indoor environments
Nitrous oxide (N_2O)	44.01	1.98	- Has similar density and molecular weight as CO_2
Carbon dioxide (CO_2)	44.01	1.87	- Bio-contaminant generated during exhalation - Biomarker of exhaled droplet nuclei[138]
1,1,1,2-Tetrafluoroethane ($C_2H_2F_4$)	102.03	4.25	- Insignificant environmental effects - Does not exist in typical indoor environments

Aerosol and smoke visualization experiment

In aerosol experiments, aerosolized particles of various sizes, usually smaller than or equal to 3 μm, are generated by the monodisperse aerosol generators to identify the distribution of airborne contaminants and evaluate the ventilation performance.[63,99,106,113] Other studies utilized non-monodisperse aerosols in their experiments. However, they targeted measuring the particle concentration within a specific size range, with a particular interest in particles smaller than 3 μm. This size range is commonly associated with virus-laden aerosols and is considered crucial in understanding the airborne transmission of viruses.[107,109,116] In studies in which the particle filtration efficiency of the HEPA filter or personal protected equipment (PPE) was concerned, for example, Sun et al.[87], Mead and Johnson[95] and Rogak et al.[99], aerosols experiments were also employed.

Besides tracking the spatial and temporal variations of the aerosols in the rooms, small aerosols of non-specific sizes (i.e., smoke) were deployed and captured by video or high-speed camera in some studies to identify the formation of instantaneous airflow patterns and vortices induced by human movement. For example, smoke visualization was adopted in both Kalliomäki et al.[119] and Kalliomäki et al.[123] to illustrate the effects of the door opening, passage, temperature difference, and directional airflow on flow patterns. Figure 6 exhibits the still images obtained from the smoke visualization experiment by Kalliomäki et al.[119].

While tracer gases may be preferable in actual hospital environments due to the potential health consequences of using small-sized aerosols in experiments, using aerosols as surrogates for bioaerosols in experimental studies offers several technical advantages. Firstly, aerosols are easily generated, and their concentration can be detected and measured accurately using cheaper sampling instruments compared to those used to measure tracer gas concentration.[142] This allows for high-resolution spatial and temporal analysis of particle concentration in the environment, enabling researchers to obtain detailed information on the behaviour of airborne contaminants.

Furthermore, aerosols can be used to simulate a wide range of particle sizes, densities and shapes, making them a versatile tool for studying the behaviour of airborne contaminants under various environmental conditions and influencing factors. This capability is particularly advantageous for researchers seeking to investigate the airborne transmission of viruses via aerosols. In addition, when evaluating the filtration performance of air filters or air purification devices, experiments must be conducted using aerosols instead of tracer gas for a more accurate assessment of the effectiveness of filtration methods in removing or reducing airborne pollutants.

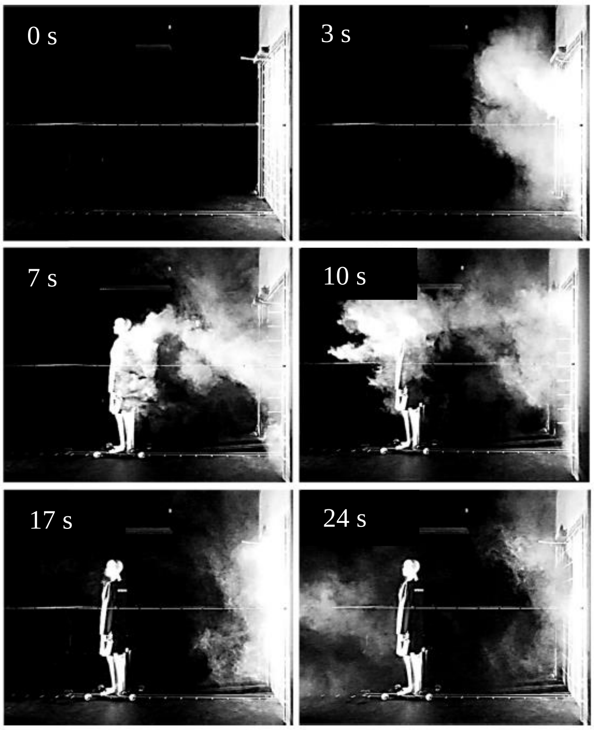


Figure 6. Still images from a smoke visualization experiment demonstrating the airflow patterns induced by opening a single hinged door and manikin passage with a ventilation rate of 12 ACH and a flow rate differential of 18 L/s.[119]

Overall, using aerosols as surrogates for bioaerosols in experimental studies provides valuable insights into the behaviour of airborne contaminants and offers several technical advantages over tracer gases.

Bioaerosol experiment

In a few studies, artificial bacterial contaminants were generated to simulate a more realistic and viable movement of bioaerosols in mock-up hospital environments. Using real bioaerosols for experimental purposes presents technical challenges due to the lack of specialized facilities and equipment for their preparation and testing. These challenges include the need for biological testing chambers, biological safety laboratories, specialized aerosol generators, samplers and imaging systems, and the expertise required for bioaerosol identification and analysis. Additionally, experimental protocols must be carefully designed to ensure reproducibility, and the selection of bioaerosols used in the experiment must consider both representativeness and safety concerns.

Due to the technical difficulties and safety concerns associated with bioaerosols, only a few studies have employed this approach. Despite these challenges, bioaerosols offer several advantages over surrogate aerosols, including a more realistic simulation of environmental conditions and the behaviour of airborne contaminants. For instance, the movement and correlation of bioaerosols were compared with aerosols to evaluate the feasibility of using real-time aerosol measurement for bioaerosol exposure and risk assessment.[134] Bioaerosols were also used in disinfection studies to evaluate the fractional reduction of pathogenic aerosol concentrations with or without the technology. Figure 7 shows the measurement results of applying a UVC air disinfection system in the HVAC system by de Souza et al.[126] with a significant reduction in the growth of microorganisms.

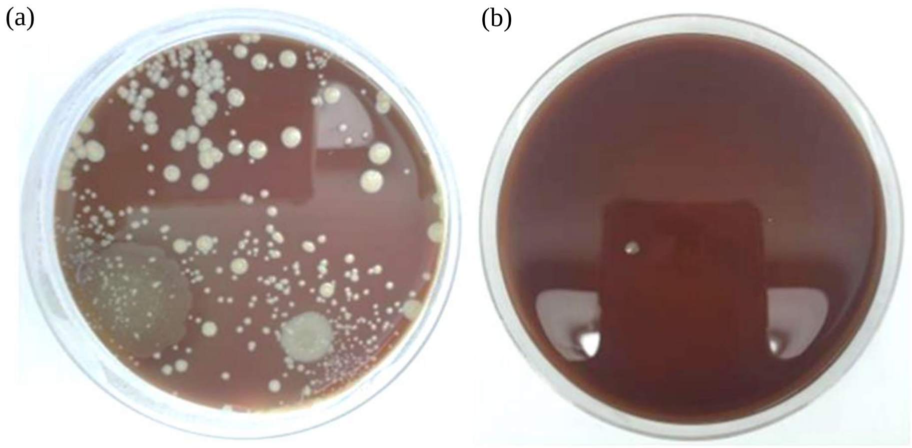


Figure 7. Petri dishes incubated at 35±2°C demonstrated a significant reduction in microorganism growth after the HVAC air exposed to the UVC equipment for 24 hours, (a) without UVC; (b) with UVC.[126]

Other experiments

Flow visualization experiments using small-scale physical analogues with water were performed in a few studies. Like smoke visualization experiments, it provides a visual representation of airflow patterns, which can help researchers or designers better understand airflow behaviour in a given space. These experiments can be conducted relatively inexpensively and quickly compared to other methods, which is especially useful for identifying potential flow obstructions or areas of high turbulence that can impact indoor air quality and the overall effectiveness of ventilation systems. However, one disadvantage of using water analogues is that the effects of ventilation cannot be fully demonstrated due to differences in physical properties. Besides, flow visualization experiments may not be able to capture the interactions between airflows and other environmental factors such as temperature and humidity. As a result, the findings obtained from these experiments can only indicate potential airflow in a given space. An example of using food dye in the water to visualize the air movement by Tang et al.[120] is shown in Figure 8.

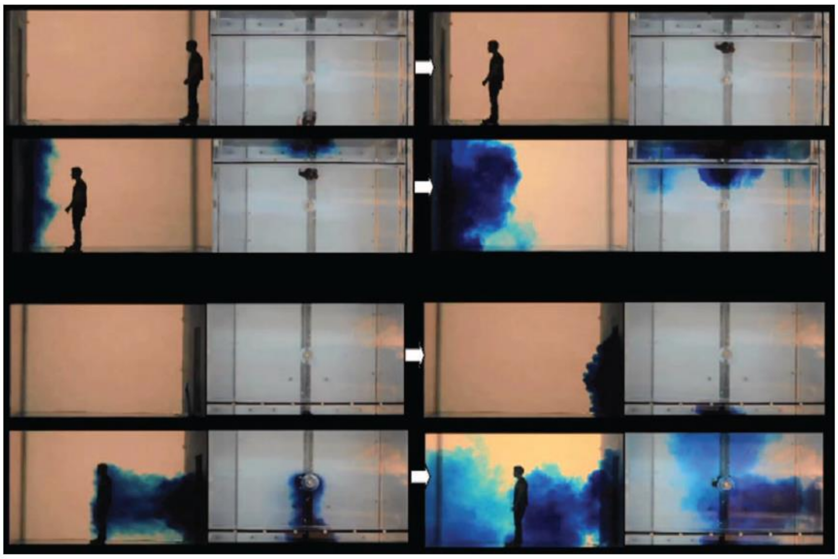


Figure 8. Snapshots of food dye movement due to door-opening motions and actions of the manikin.[120]

Sometimes due to practical limitations, especially for studies conducted in real hospitals, rather than introducing tracer gas or aerosols into the environment to identify the variations under different scenarios, field measurements were done to evaluate the effects of various experimental conditions. For instance, to investigate the influence of human movements and actions on the dispersion of airborne bacteria under mixing ventilation, Annaqeeb et al.[125] collected depositing bacteria using agar plates during three mock-up hip arthroplasty procedures in an actual operating room. Besides bioaerosol concentrations, environmental conditions such as ACH, air velocity and particle levels are often measured to assess the influences of experimental scenarios. Many factors that were considered in the experiment can influence environmental conditions. Therefore, it is necessary to conduct repeated experiments to ensure the validity of the results.

Limitations

This systematic review aimed to identify and categorize the research methodologies, research interests, aspects of airborne transmission, experimental results, conclusions and limitations of existing studies on experimental methods for studying airborne transmission in hospitals. However, it is important to acknowledge certain limitations of this review. Firstly, this review has a limited scope, explicitly focusing on experimental studies related to airborne transmission in hospitals, and did not consider other aspects of environmental quality, such as thermal comfort and air quality in healthcare settings. Additionally, due to limited information presented in most studies, the quality of the experiments in terms of replicability and accuracy of the reviewed studies was not assessed, potentially impacting the validity and reliability of the findings. Lastly, the generalizability of the findings may be limited, as the studies reviewed were conducted in various locations and under different conditions.

However, this systematic review provides a comprehensive summary of the research trends, objectives, research interests, experimental methods and limitations of existing empirical studies related to airborne transmission in hospitals. These findings can provide valuable insights and future research directions for fellow researchers in the field.

Sampling difficulties

Sampling difficulties due to high experimental costs are significant hurdles for large-scale experimental studies. Therefore, experimental scenarios are often limited in cases, controlled parameters and experimental scales. Experimental studies that employed tracer gases often had a limited number of sampling points, typically less than nine,[71,83,112] even in studies conducted throughout an entire hospital floor.[103] This sampling limitation can be attributed to the high cost of tracer gas sampling instruments.[138] Similarly, in aerosol experiments, the number of sampling points was often limited, [77,81,91,95] with the highest reported number of sampling points being 13.[116] Some studies recognized the need for more experiments to produce high-resolution spatial variations of tracer gas, aerosols or environmental conditions due to the limited availability of sampling equipment.[64,72,103] Overall, the experimental studies reviewed highlight the practical limitations and challenges associated with sampling and data collection.

The other sampling limitation is not being able to conduct the experiments in real hospitals or under realistic situations. Amongst the studies reviewed, approximately 46% of them were conducted in actual hospital settings, while the remaining studies employed mock-up rooms or physical analogues for their experimental set-up. This distribution of experimental settings underscores the practical difficulties of conducting experimental studies in real healthcare environments. Mock-up rooms or physical analogues can provide a controlled and replicable experimental set. At the same time, real hospital settings offer a more realistic representation of healthcare facilities' complex and dynamic environmental conditions. As a result, some experiments reviewed adopted the steady-state assumption, which provides valuable insights but a limited representation of the actual dynamic indoor condition and situation.[83,112]

Limited experimental scenarios, uncontrolled/ unconsidered factors

Experimental studies often encounter the problem of uncontrolled or unconsidered factors that can influence the results.[116] Although the hospitals are designed and configured to meet ventilation guidelines and assumed to be well-mixed, the unique environmental conditions, such as the layout and presence of medical equipment and staff, could greatly affect the uniformity, creating unique and dynamic airflow patterns with movements involved.[99] The presence and movements of patients and medical staff and transient conditions were often ignored[83,95,103,112] and even did, the body and the movements were not modelled realistically.[71,91,110,119] Many studies reviewed in this systematic review had limited experimental scenarios due to high implementation costs. Typically, the number of case scenarios reported in the studies ranged from two to seven, with a few exceptions, such as Cadnum et al.[115] with 13 cases and Rogak et al.[99] with 41 cases. The relatively simple experimental setup in the latter two studies facilitated more experimental scenarios. The practical and financial constraints often limit the scale and number of experiments that can be conducted. Considering and controlling all possible influencing factors and conditions is also not feasible. As a result, experimental results can only serve as a reference for specific cases and cannot be generalized to all scenarios.[95]

Nature of experimental mediums

Despite the extensive use of tracer gas and aerosols as surrogates of bioaerosols in experimental studies, one must remember that the aerodynamics of different bioaerosols may differ from tracer gas or small-size aerosols. In addition, the generation of exhaled droplet nuclei containing infectious pathogens through respiratory processes is complex. Depending on the modes of exhalation, the effects of gravity and environmental conditions, exhaled droplets will adopt different sizes and be subjected to the influence of airflow of various degrees.[135,136] The experimental results obtained from tracer gas or small-size aerosols experiment cannot be applied to larger-size droplet particles or implied in the case of actual biological contaminants.[71,85,90] Nonetheless, for various reasons, including the resource availability, cost of the experiment and safety concerns, tracer gas and aerosols are good and practical indications of the movement of bioaerosols in hospital environments.

Future research directions

Use of IoT-based sampling devices

This review identified the need for more existing experimental studies with limited sampling equipment, thus were only able to produce a spatial understanding of the dispersion of aerosols or tracer gas with low resolution. With the advancement of the internet-of-things (IoT), many IoT applications using low-cost sensors for environmental monitoring have been developed to measure fine particles with diameters of 2.5 μm and 1.0 μm or less ($PM_{2.5}$ and $PM_{1.0}$).[139] An IoT-based wireless sensor grid was recently expanded to identify spatial and temporal variations of tracer gas.[140] These technologies could help enhance the experimental capacity and produce high-resolution spatial and temporal understandings of the dispersion of bioaerosols with a low implementation cost.

Real-time monitoring of bioaerosols (or their surrogates)

Monitoring the concentration of bioaerosols in the air in real-time or using surrogates to represent the relative levels of airborne microbes enables hospital operators to swiftly identify the risks of infection and provide fast and appropriate responses to mitigate airborne transmission. Attempts to identify the associations between common air pollutants and airborne microbes need to be increased. More experiments should be done to determine the suitable indicators for microbial contaminants that can be monitored in real-time. With the recent advancements in low-cost air quality sensors, wireless sensing networks can be implemented in hospitals as a real-time surveillance strategy for airborne transmission and infection risk.[141]

Field surveys for realistic experiments

Experimental studies with realistic conditions are scarce. Replicating the typical room conditions, layouts, operational practices, ventilation configurations and performances, medical procedures and movement of staff inside a hospital can provide realistic data for more reliable experiments that can reflect real case scenarios. Field surveys and epidemiological evidence on a case-by-case basis in real hospitals will be required to obtain the relevant information.

More interdisciplinary studies

Interdisciplinary studies could greatly benefit and accelerate research and discovery in this field. Experimentalists shall work closely with theocratical mathematicians to identify the influence of ventilation, environmental conditions and human presence on airborne transmission pathways and the risk of hospital infections. While experimental studies are limited in the number of case scenarios and factors to be considered due to resource restrictions, experimental results can be used to validate simulation models generated by computational methods. Interdisciplinary efforts from researchers, building engineers, healthcare professionals and the government are also crucial for identifying feasible, practical and helpful engineering solutions and management practices to minimize hospital airborne transmission.

Conclusion

Experimental studies are crucial in research as they provide physical evidence to support engineering decisions and real-case data for validating theoretical studies. To summarize current knowledge and experimental evidence on the effects of building ventilation and environmental factors on airborne transmission in hospitals, a systematic review was conducted to identify and categorize the research methodologies, research interests, aspects of airborne transmission, experimental results, conclusion and limitations of existing studies. Following the PRISMA system, 72 journal and conference articles published from 1995 to Mar 2023 were selected from 2,153 Web of Science, Scopus and PubMed search results. Keywords co-occurrence analysis suggested “airborne transmission”, “infection control” and “ventilation” as the three main keywords used. Annual publication records of the studies reviewed showed a steady but slow growth of experimental research in the field.

The selected articles were assessed individually to identify the objectives, research interests, experimental methods, useful findings and limitations. Most looked into the effects of ventilation systems, strategies and configurations on airborne transmission. Personal or localized ventilation units and air purifiers were also assessed. Some studies aimed to better understand bioaerosols' spatial and temporal dispersion under the combined effects of environmental factors and emission scenarios, with a particular interest in the effects of human movement. Studies on air disinfection technologies in hospitals have gained recent attention, potentially due to the COVID-19 pandemic. Typically, tracer gas and small-size aerosols were used in the experiments as the surrogates of airborne pathogens. Alternatively, real aerosolized bacteria might be employed in mock-up hospitals. Flow visualization using small-scale physical analogues or smoke visualization sometimes were used to illustrate the visible airflow patterns. With practical limitations, field measurements of bio-contaminants or environmental conditions might be carried out to evaluate the effects of changing experimental conditions.

Some useful insights were extracted from the studies reviewed. Researchers’ views on the optimal or effective quantity of ACH to reduce airborne infection were contradictory. Still, it was acknowledged that the relative position of the ventilation supply and exhaust, the infected patient and the susceptible, and the posture of the source patient were critical influencing factors to the dispersion of the bioaerosols. Personal or localized ventilation and disinfection technologies such as portable and upper-room UVGI could provide some degree of protection from airborne infection. The effectiveness, however, depends on several environmental and practical factors, such as the position of the devices, ventilation rates, target microorganisms, etc. Many factors were found to influence the dispersion patterns of the bioaerosols, for example, ventilation strategies and configurations, room layouts, source positions, postures and exhalation modes. Door opening and human passage could also affect the airflow patterns. The use of directional airflows at the doorway may be able to limit the undesirable effects.

This review revealed some limitations and challenges encountered by existing studies. Sampling difficulties were faced due to the limited availability of sampling equipment and experimental facilities. High experimental costs also limited the scale and number of experimental scenarios considered in the studies. Some influencing factors, such as healthcare staff presence and movement, were not considered or controlled for simplicity. Notably, some may question the use of tracer gas or aerosols in the experiments as they are not bioaerosols. Nonetheless, with the concerns of resource, cost and safety requirements, they remain suitable mediums for experimentation.

On a final note, some future research directions were proposed. Using IoT-based sampling devices for experiments and real-time monitoring of bioaerosols or their surrogates can enhance the experimental capacity and provide a more thorough understanding of bioaerosol's spatial and temporal distribution and the associated infection risks. Field surveys on a case-by-case basis shall be conducted in hospitals to gather relevant information for realistic experiments. Lastly, more interdisciplinary studies and collaborations are needed to provide practical and effective solutions to minimize hospital airborne transmission.

Authors' contribution

Tsz Wun Tsang: Conceptualization, Methodology, Investigation, Validation, Formal analysis, Writing - Original Draft, Visualization. Ling Tim Wong: Project administration, Supervision, Writing - Review & Editing. Kwok Wai Mui: Funding acquisition, Project administration, Supervision, Writing - Review & Editing.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was financially supported by a grant from the Collaborative Research Fund (CRF) COVID-19 and Novel Infectious Disease (NID) Research Exercise, the Research Grants Council of the Hong Kong Special Administrative Region, China (Project no. PolyU P0033675/C5108-20G) and the Research Institute for Smart Energy (RISE) Matching Fund (Project no. P0038532).

References

1. Weiner DL, Balasubramaniam V, Shah SI, Javie JR. COVID-19 impact on research, lessons learned from COVID-19 research, implications for pediatric research. *Pediatr Res* 2020; 88: 148–150.

2. Lewis D. Why the WHO took two years to say COVID is airborne. *Nature* 2022; 604: 26–31.

3. Vass WB, Lednicky JA, Shankar SN, Fan ZH, Eiguren-Fernandez A, Wu CY. Viable SARS-CoV-2 Delta variant detected in aerosols in a residential setting with a self-isolating college student with COVID-19. *J Aerosol Sci* 2022; 165: 106038.

4. Lednicky JA, Lauzardo M, Fan ZH, Jutla A, Tilly TB, Gangwar M, Usmani M, Shankar SN, Mohamed K, Eiguren-Fernandez A, Stephenson CJ, Alam MM, Elbadry MA, Loeb JC, Subramaniam K, Waltzek TB, Cherabuddi K, Morris JG Jr, Wu CY. Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients. *Int J Infect Dis* 2020; 100: 476–482.

5. Lu J, Gu J, Li K, Xu C, Su W, Lai Z, Zhou D, Yu C, Xu B, Yang Z. COVID-19 Outbreak Associated with Air Conditioning in Restaurant, Guangzhou, China, 2020. *Emerg Infect Dis* 2020; 26(7): 1628–1631.

6. Kwon KS, Park JI, Park YJ, Jung DM, Ryu KW, Lee JH. Evidence of Long-Distance Droplet Transmission of SARS-CoV-2 by Direct Air Flow in a Restaurant in Korea. *J Korean Med Sci* 2020; 35(46): e415.

7. Li Y, Qian H, Hang J, Chen X, Cheng P, Ling H, Wang S, Liang P, Li J, Xiao S, Wei J, Liu L, Cowling BJ, Kang M. Probable airborne transmission of SARS-CoV-2 in a poorly ventilated restaurant. *Build Environ* 2021; 196: 107788.

8. Shen Y, Li C, Dong H, Wang Z, Martinez L, Sun Z, Handel A, Chen Z, Chen E, Ebell MH, Wang F, Yi B, Wang H, Wang X, Wang A, Chen B, Qi Y, Liang L, Li Y, Ling F, Chen J, Xu G. Community Outbreak Investigation of SARS-CoV-2 Transmission Among Bus Riders in Eastern China. *JAMA Intern Med* 2020; 180(12): 1665–1671.

9. Nissen K, Krambrich J, Akaberi D, Hoffman T, Ling J, Lundkvist Å, Svensson L, Salaneck E. Long-distance airborne dispersal of SARS-CoV-2 in COVID-19 wards. I 2020; 10: 19589.

10. Hwang SE, Chang JH, Oh B, Heo J. Possible aerosol transmission of COVID-19 associated with an outbreak in an apartment in Seoul, South Korea, 2020. *Int J Infect Dis* 2021; 104: 73–76.

11. Cheng VC, Wong SC, Au AK, Zhang C, Chen JH, So SY, Li X, Wang Q, Lu KK, Lung DC, Chuang VW, Schuldenfrei E, Siu GK, To KK, Li Y, Yuen KY. Explosive outbreak of SARS-CoV-2 Omicron variant is associated with vertical transmission in high-rise residential buildings in Hong Kong. *Build Environ* 2022; 221: 109323.

12. Al-Omari B, Ahmad T, Al-Rifai RH. SARS-CoV-2 and COVID-19 Research Trend during the First Two Years of the Pandemic in the United Arab Emirates: A PRISMA-Compliant Bibliometric Analysis. *Int J Environ Res Public Health* 2022; 19: 7753.

13. Li Y, Leung GM, Tang JW, Yang X, Chao CY, Lin JZ, Lu JW, Nielsen PV, Niu J, Qian H, Sleigh AC, Su HJ, Sundell J, Wong TW, Yuen PL. Role of ventilation in airborne transmission of infectious agents in the built environment - a multidisciplinary systematic review. *Indoor Air* 2007; 17(1): 2–18.

14. Tsang TW, Mui KW, Wong LT. Computational Fluid Dynamics (CFD) studies on airborne transmission in hospitals: A review on the research approaches and the challenges. *J Build Eng* 2022; 63: 105533.

15. Daegling DJ, Hylander WL. Experimental observation, theoretical models, and biomechanical inference in the study of mandibular form. *Am J Phys Anthropol* 2000; 112(4): 541–551.

16. Oberkampf WL, Trucano TG. Verification and validation in computational fluid dynamics. *Prog Aerosp Sci* 2002; 38(3): 209–272.

17. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). 2023 ASHRAE Handbook – HVAC Applications. New York: The Society.

18. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE, Chou R, Glanville J, Grimshaw JM, Hróbjartsson A, Lalu MM, Li T, Loder EW, Mayo-Wilson E, McDonald S, McGuinness LA, Stewart LA, Thomas J, Tricco AC, Welch VA, Whiting P, Moher D. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 2021; 372: n71.

19. Rayegan S, Shu C, Berquist J, Jeon J, Zhou LG, Wang LL, Mbareche H, Tardif P, Ge H. A review on indoor airborne transmission of COVID-19–modelling and mitigation approaches. *J Build Eng* 2022; 64: 105599.

20. Chen CY, Chen PH, Chen JK, Su TC. Recommendations for ventilation of remodeled negative-pressure isolation wards for COVID-19 patients: A comparison of international guidelines. *J Formos Med Assoc* 2023; 122(2): 91–97.

21. Patel J, McGain F, Bhatelia T, Wang S, Sun B, Monty J, Pareek V. Vented Individual Patient (VIP) Hoods for the Control of Infectious Airborne Diseases in Healthcare Facilities. *Eng (Beijing)* 2022; 15: 126–132.

22. Rhee C, Baker MA, Klompas M. Prevention of SARS-CoV-2 and respiratory viral infections in healthcare settings: current and emerging concepts. *Curr Opin Infect Dis* 2022; 35(4): 353–362.

23. Ye J, Lin C, Liu J, Ai Z, Zhang G. Systematic summary and analysis of Chinese HVAC guidelines coping with COVID-19. *Indoor Built Environ* 2022; 31(5): 1176–1192.

24. Andalib E, Faghani M, Zia Ziabari SM, Shenagari M, Salehiniya H, Keivanlou MH, Rafat Z. The Effectiveness of the Anteroom (Vestibule) Area on Hospital Infection Control and Health Staff Safety: A Systematic Review. *Front Public Health* 2022; 10: 828845.

25. Clementini M, Raspini M, Barbato L, Bernardelli F, Braga G, Di Gioia C, Littarru C, Oreglia F, Brambilla E, Iavicoli I, Pinchi V, Landi L, Marco Sforza N, Cavalcanti R, Crea A, Cairo F. Aerosol transmission for SARS-CoV-2 in the dental practice. A review by SIdP Covid-19 task-force. *Oral Dis* 2022; 28(Suppl 1): 852–857.

26. Klompas M, Milton DK, Rhee C, Baker MA, Leekha S. Current Insights into Respiratory Virus Transmission and Potential Implications for Infection Control Programs: A Narrative Review. *Ann Intern Med* 2021; 174(12): 1710–1718.

27. Dai R, Liu S, Li Q, Wu H, Wu L, Ji C. A systematic review and meta-analysis of indoor bioaerosols in hospitals: The influence of heating, ventilation, and air conditioning. *PLoS One* 2021; 16(12): e0259996.

28. Shbaklo N, Lupia T, de Rosa FG, Corcione S. Infection Control in the Era of COVID-19: A Narrative Review. *Antibiotics (Basel)* 2021; 10(10): 1244.

29. Pasquier J, Villalta O, Sarria Lamorú S, Balagué C, Vilallonga R, Targarona EM. Are Smoke and Aerosols Generated During Laparoscopic Surgery a Biohazard? A Systematic Evidence-Based Review. *Surg Innov* 2021; 28(4): 485–495.

30. Aghalari Z, Dahms HU, Sosa-Hernandez JE, Oyervides-Muñoz MA, Parra-Saldívar R. Evaluation of SARS-COV-2 transmission through indoor air in hospitals and prevention methods: A systematic review. *Environ Res* 2021; 195: 110841.

31. Noorimotlagh Z, Jaafarzadeh N, Martínez SS, Mirzaee SA. A systematic review of possible airborne transmission of the COVID-19 virus (SARS-CoV-2) in the indoor air environment. *Environ Res* 2021; 193: 110612.

32. Atiyani R, Mustafa S, Alsari S, Darwish A, Janahi EM. Clearing the air about airborne transmission of SARS-CoV-2. *Eur Rev Med Pharmacol Sci* 2021; 25(21): 6745–6766.

33. Gola M, Caggiano G, de Giglio O, Napoli C, Diella G, Carlucci M, Carpagnano LF, D'Alessandro D, Joppolo CM, Capolongo S, Montagna MT. SARS-CoV-2 indoor contamination: considerations on anti-COVID-19 management of ventilation systems, and finishing materials in healthcare facilities. *Ann Ig* 2021; 33(4): 381–392.

34. Rabaan AA, Al-Ahmed SH, Al-Malkey M, Alsubki R, Ezzikouri S, Al-Hababi FH, Sah R, Al Mutair A, Alhumaid S, Al-Tawfiq JA, Al-Omari A, Al-Qaaneh AM, Al-Qahtani M, Tirupathi R, Al Hamad MA, Al-Baghli NA, Sulaiman T, Alsubait A, Mehta R, Abass E, Alawi M, Alshahrani F, Shrestha DB, Karobari MI, Pecho-Silva S, Arteaga-Livias K, Bonilla-Aldana DK, Rodriguez-Morales AJ. Airborne transmission of SARS-CoV-2 is the dominant route of transmission: droplets and aerosols. *Infez Med* 2021; 29(1): 10–19.

35. Jangir A, Siddiquee MA, Mankotia S, Tiwari V, Vyas G, Choudhary R. A comparative study of ventilation system used for the bacteria prevention in operation room in healthcare units. *Mater Today* 2022; 50: 2355–2360.

36. Al-Benna S. Negative pressure rooms and COVID-19. *J Perioper Pract* 2021; 31(1-2): 18–23.

37. Tang S, Mao Y, Jones RM, Tan Q, Ji JS, Li N, Shen J, Lv Y, Pan L, Ding P, Wang X, Wang Y, MacIntyre CR, Shi X. Aerosol transmission of SARS-CoV-2? Evidence, prevention and control. *Environ Int* 2020; 144: 106039.

38. Schünemann HJ, Khabsa J, Solo K, Khamis AM, Brignardello-Petersen R, El-Harakeh A, Darzi A, Hajizadeh A, Bognanni A, Bak A, Izcovich A, Cuello-Garcia CA, Chen C, Borowiack E, Chamseddine F, Schünemann F, Morgano GP, Muti-Schünemann GEU, Chen G, Zhao H, Neumann I, Brozek J, Schmidt J, Hneiny L, Harrison L, Reinap M, Junek M, Santesso N, El-Khoury R, Thomas R, Nieuwlaat R, Stalteri R, Yaacoub S, Lotfi T, Baldeh T, Piggott T, Zhang Y, Saad Z, Rochwerg B, Perri D, Fan E, Stehling F, Akl IB, Loeb M, Garner P, Aston S, Alhazzani W, Szczeklik W, Chu DK, Akl EA. Ventilation Techniques and Risk for Transmission of Coronavirus Disease, Including COVID-19: A Living Systematic Review of Multiple Streams of Evidence. *Ann Intern Med* 2022; 175(1): W6–7.

39. Diel R, Nienhaus A, Witte P, Ziegler R. Protection of healthcare workers against transmission of Mycobacterium tuberculosis in hospitals: a review of the evidence. *ERJ Open Res* 2020; 6(1): 00317–2019.

40. Asmarawati TP, Arfijanto MV, Hadi U, Miftahussurur M. Healthcare associated COVID-19 transmission: Strategies to prevent. *New Armen Med J* 2020; 14(4): 29–36.

41. Judson SD, Munster VJ. Nosocomial Transmission of Emerging Viruses via Aerosol-Generating Medical Procedures. *Viruses* 2019; 11(10): 940.

42. Stockwell RE, Ballard EL, O'Rourke P, Knibbs LD, Morawska L, Bell SC. Indoor hospital air and the impact of ventilation on bioaerosols: a systematic review. *J Hosp Infect* 2019; 103(2): 175–184.

43. Qian H, Zheng X. Ventilation control for airborne transmission of human exhaled bio-aerosols in buildings. *J Thorac Dis* 2018; 10(Suppl 19): S2295–2304.

44. Lyons PG, Kollef MH. Prevention of hospital-acquired pneumonia. *Curr Opin Crit Care* 2018;24(5):370–378.

45. Wei J, Li Y. Airborne spread of infectious agents in the indoor environment. *Am J Infect Control* 2016;44(9 Suppl):S102–8.

46. English TR. A Brief History of Health-Care Ventilation. *ASHRAE J* 2016; 58(6): 52–60.

47. Nardell EA. Indoor environmental control of tuberculosis and other airborne infections. *Indoor Air* 2016; 26(1): 79–87.

48. Li Y, Tang J, Noakes C, Hodgson MJ. Engineering control of respiratory infection and low-energy design of healthcare facilities. *Sci Technol Built Environ* 2015; 21(1): 25–34.

49. Hobday RA, Dancer SJ. Roles of sunlight and natural ventilation for controlling infection: historical and current perspectives. *J Hosp Infect* 2013; 84(4): 271–282.

50. Jacob JT, Kasali A, Steinberg JP, Zimring C, Denham ME. The role of the hospital environment in preventing healthcare-associated infections caused by pathogens transmitted through the air. *HERD* 2013; 7(Suppl 1): 74–98.

51. Li Y, Nielsen PV, Sandberg M. Displacement ventilation in hospital environments. *ASHRAE J* 2011; 53(6): 86–89.

52. Eames I, Tang JW, Li Y, Wilson P. Airborne transmission of disease in hospitals. *J R Soc Interface* 2009; 6(Suppl 6): S697–702.

53. Clark RP, de Calcina-Goff ML. Some aspects of the airborne transmission of infection. *J R Soc Interface* 2009; 6(Suppl 6): S767–782.

54. Humphreys H. Control and prevention of healthcare-associated tuberculosis: the role of respiratory isolation and personal respiratory protection. *J Hosp Infect* 2007; 66(1): 1–5.

55. Tang JW, Li Y, Eames I, Chan PK, Ridgway GL. Factors involved in the aerosol transmission of infection and control of ventilation in healthcare premises. *J Hosp Infect* 2006; 64(2): 100–114.

56. Cacciari P, Giannoni R, Marcelli E, Cercenelli L. Considerations on isolation rooms and alternative pressure ventilation systems. *Ann Ig* 2004; 16(6): 777–801.

57. Dharan S, Pittet D. Environmental controls in operating theatres. *J Hosp Infect* 2002; 51(2): 79–84.

58. Beggs CB, Donnelly JK, Kerr KG, Sleigh PA, Mara DD, Cairns G. The use of engineering controls to disinfect Mycobacterium tuberculosis and airborne pathogens in hospital buildings. *Indoor Built Environ* 2000; 9(1): 17–27.

59. Eickhoff TC. Airborne nosocomial infection: a contemporary perspective. *Infect Control Hosp Epidemiol* 1994; 15(10): 663–672.

60. Rousseau CP, Rhodes WW. HVAC system provisions to minimize the spread of tuberculosis bacteria. *ASHRAE Trans* 1993; 99: 1201.

61. Radhakrishnan S, Erbis S, Isaacs JA, Kamarthi S. Novel keyword co-occurrence network-based methods to foster systematic reviews of scientific literature. *PLoS One* 2017; 12(9): e0185771.

62. Short CA, Woods AW, Drumright L, Zia R, Mingotti N. An alternative approach to delivering safe, sustainable surgical theatre environments. *Build Cities* 2022; 3(1): 316–333.

63. Yin Y, Xu W, Gupta JK, Guity A, Marmion P, Manning A, Gulick B, Zhang XS, Chen QY. Experimental study on displacement and mixing ventilation systems for a patient ward. *HVAC&R Res* 2009; 15(6): 1175–1191.

64. Escombe AR, Ticona E, Chávez-Pérez V, Espinoza M, Moore DA. Improving natural ventilation in hospital waiting and consulting rooms to reduce nosocomial tuberculosis transmission risk in a low resource setting. *BMC Infect Dis* 2019; 19: 1–7.

65. Cao G, Nilssen AM, Cheng Z, Stenstad LI, Radtke A, Skogås JG. Laminar airflow and mixing ventilation: Which is better for operating room airflow distribution near an orthopedic surgical patient? *Am J Infect Control* 2019; 47(7): 737–743.

66. Gilkeson CA, Camargo-Valero MA, Pickin LE, Noakes CJ. Measurement of ventilation and airborne infection risk in large naturally ventilated hospital wards. *Build Environ* 2013; 65: 35–48.

67. Weng CL, Kau LJ. Planning and design of a full-outer-air-intake natural air-conditioning system for medical negative pressure isolation wards. *J Healthcare Eng* 2021: 8872167.

68. Tung YC, Hu SC, Tsai TI, Chang IL. An experimental study on ventilation efficiency of isolation room. *Build Environ* 2009; 44(2): 271–279.

69. Grosskopf K, Mousavi E. Bioaerosols in health-care environments. *ASHRAE J* 2014; 56(8): 22–31.

70. Liang CC, Wu FJ, Chien TY, Lee ST, Chen CT, Wang C, Wan GH. Effect of ventilation rate on the optimal air quality of trauma and colorectal operating rooms. *Build Environ* 2020; 169: 106548.

71. Berlanga FA, Olmedo I, de Adana MR, Villafruela JM, San José JF, Castro F. Experimental assessment of different mixing air ventilation systems on ventilation performance and exposure to exhaled contaminants in hospital rooms. *Energy Build* 2018; 177: 207–219.

72. Kong X, Guo C, Lin Z, Duan S, He J, Ren Y, Ren J. Experimental study on the control effect of different ventilation systems on fine particles in a simulated hospital ward. *Sustain Cities Soc* 2021; 73: 103102.

73. Bolashikov ZD, Melikov AK, Kierat W, Popiołek Z, Brand M. Exposure of health care workers and occupants to coughed airborne pathogens in a double-bed hospital patient room with overhead mixing ventilation. *HVAC&R Res* 2012; 18(4): 602–615.

74. Miller SL, Clements N, Elliott SA, Subhash SS, Eagan A, Radonovich LJ. Implementing a negative-pressure isolation ward for a surge in airborne infectious patients. *Am J Infect Control* 2017; 45(6): 652–659.

75. Choi N, Yamanaka T, Kobayashi T, Ihama T, Wakasa M. Influence of vertical airflow along walls on temperature and contaminant concentration distributions in a displacement-ventilated four-bed hospital ward. *Build Environ* 2020; 183: 107181.

76. Dettenkofer M, Scherrer M, Hoch V, Glaser H, Schwarzer G, Zentner J, Daschner ED. Shutting down operating theater ventilation when the theater is not in use: infection control and environmental aspects. *Infect Control Hosp Epidemiol* 2003; 24(8): 596–600.

77. Offermann FJ, Eagan A, Offermann AC, Subhash SS, Miller SL, Radonovich LJ. Potential airborne pathogen transmission in a hospital with and without surge control ventilation system modifications. *Build Environ* 2016; 106: 175–180.

78. Feng L, Zhou B, Xu Y, Xue K, Li Y, Zhang R, Peng W, Huang R. Theoretical investigation and experimental validation on transient variation of particle concentration in a simulated consulting room in hospital. *Build Environ* 2017; 117: 1–10.

79. Olmedo I, Berlanga FA, Villafruela JM, de Adana MR. Experimental variation of the personal exposure in a hospital room influenced by wall heat gains. *Build Environ* 2019; 154: 252–262.

80. Liu Z, Wang L, Rong R, Fu S, Cao G, Hao C. Full-scale experimental and numerical study of bioaerosol characteristics against cross-infection in a two-bed hospital ward. *Build Environ* 2020; 186: 107373.

81. Therkorn J, Drewry D, Pilholski T, Shaw-Saliba K, Bova G, Maragakis LL, Garibaldi B, Sauer L. Impact of air-handling system exhaust failure on dissemination pattern of simulant pathogen particles in a clinical biocontainment unit. *Indoor Air* 2019; 29(1): 143–155.

82. Nielsen PV, Li Y, Buus M, Winther FV. Risk of cross-infection in a hospital ward with downward ventilation. *Build Environ* 2010; 45(9): 2008–2014.

83. Aganovic A, Cao G. Evaluation of airborne contaminant exposure in a single-bed isolation ward equipped with a protected occupied zone ventilation system. *Indoor Built Environ* 2019; 28(8): 1092–1103.

84. Pasquarella C, Sansebastiano GE, Ferretti S, Saccani E, Fanti M, Moscato U, Giannetti G, Fornia S, Cortellini P, Vitali P, Signorelli C. A mobile laminar airflow unit to reduce air bacterial contamination at surgical area in a conventionally ventilated operating theatre. *J Hosp Infect* 2007; 66(4): 313–319.

85. Yang J, Sekhar C, Cheong KW, Raphael B. A time-based analysis of the personalized exhaust system for airborne infection control in healthcare settings. *Sci Technol Built Environ* 2015; 21: 172–178.

86. Bivolarova MP, Melikov AK, Mizutani C, Kajiwara K, Bolashikov ZD. Bed-integrated local exhaust ventilation system combined with local air cleaning for improved IAQ in hospital patient rooms. *Build Environ* 2016; 100: 10–18.

87. Sun C, Marriott L, Harper M, Zhou T. Evaluation of high flow local extraction for controlling aerosol plumes in operating theatres. *Phys Fluids* 2022; 34(7): 077113.

88. Shu L, Bivolarova MP, Melikov AK. Localized Ventilation Method for Providing Clean Air to Hospitalized Patients. In *E3S Web of Conferences* 2021; 246: 02003.

89. Nishimura H, Fan Y, Sakata S. New applications of a portable isolation hood for use in several settings and as a clean hood. *J Thorac Dis* 2020; 12(7): 3500–3506.

90. Yang J, Sekhar SC, Cheong KW, Raphael B. Performance evaluation of a novel personalized ventilation-personalized exhaust system for airborne infection control. *Indoor Air* 2015; 25(2): 176–187.

91. Olmedo I, Sánchez-Jiménez JL, Peci F, de Adana MR. Personal exposure to exhaled contaminants in the near environment of a patient using a personalized exhaust system. *Build Environ* 2022; 223: 109497.

92. Gopesh T, Grant AM, Wen JH, Wen TH, Criado-Hidalgo E, Connacher WJ, Friend JR, Morris TA. Vacuum exhausted isolation locker (VEIL) to reduce inpatient droplet/aerosol transmission during COVID-19 pandemic. *Infect Control Hosp Epidemiol* 2022; 43(1): 105–117.

93. Bolashikov ZD, Barova M, Melikov AK. Wearable personal exhaust ventilation: Improved indoor air quality and reduced exposure to air exhaled from a sick doctor. *Sci Technol Built Environ* 2015; 21(8): 1117–1125.

94. Persson M, van der Linden J. Wound ventilation with ultraclean air for prevention of direct airborne contamination during surgery. *Infect Control Hosp Epidemiol* 2004; 25(4): 297–301.

95. Mead K, Johnson DL. An evaluation of portable high-efficiency particulate air filtration for expedient patient isolation in epidemic and emergency response. *Ann Emerg Med* 2004; 44(6): 635–645.

96. Rutala WA, Jones SM, Worthington JM, Reist PC, Weber DJ. Efficacy of portable filtration units in reducing aerosolized particles in the size range of Mycobacterium tuberculosis. *Infect Control Hosp Epidemiol* 1995; 16(7): 391–398.

97. Qian H, Li Y, Sun H, Nielsen PV, Huang X, Zheng X. Particle removal efficiency of the portable HEPA air cleaner in a simulated hospital ward. *Build Simul* 2010; 3: 215–224.

98. Bergeron V, Chalfine A, Misset B, Moules V, Laudinet N, Carlet J, Lina B. Supplemental treatment of air in airborne infection isolation rooms using high-throughput in-room air decontamination units. *Am J Infect Control* 2011; 39(4): 314–320.

99. Rogak SN, Rysanek A, Lee JM, Dhulipala SV, Zimmerman N, Wright M, Weimer M. The effect of air purifiers and curtains on aerosol dispersion and removal in multi-patient hospital rooms. *Indoor Air* 2022; 32(10): e13110.

100. Rosenbaum RA, Benyo JS, O'Connor RE, Passarello BA, Williams DR, Humphrey BD, Ross RW, Berry JM, Krebs JG. Use of a portable forced air system to convert existing hospital space into a mass casualty isolation area. *Ann Emerg Med* 2004; 44(6): 628–634.

101. Salmonsmith J, Ducci A, Balachandran R, Guo L, Torii R, Houlihan C, Epstein R, Rubin J, Tiwari MK, Lovat LB. Use of portable air purifiers to reduce aerosols in hospital settings and cut down the clinical backlog. *Epidemiol Infect* 2023; 151: e21.

102. Lee JH, Rounds M, McGain F, Schofield R, Skidmore G, Wadlow I, Kevin K, Stevens A, Marshall C, Irving L, Kainer M, Buising K, Monty J. Effectiveness of portable air filtration on reducing indoor aerosol transmission: preclinical observational trials. *J Hosp Infect* 2022; 119: 163–169.

103. Sung M, Jo S, Lee S-E, Ki M, Choi BY, Hong J. Airflow as a Possible Transmission Route of Middle East Respiratory Syndrome at an Initial Outbreak Hospital in Korea. *Int J Environ Res Public Health* 2018; 15(12): 2757.

104. Jones LD, Chan ER, Cadnum JL, Redmond SN, Navas ME, Zabarsky TF, Eckstein EC, Kovach JD, Linger M, Zimmerman PA, Donskey CJ. Investigation of a cluster of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infections in a hospital administration building. *Infect Control Hosp Epidemiol* 2023; 44(2): 277–283.

105. Huang YC, Tu HC, Kuo HY, Shao PL, Gong YN, Weng HY, Shu HY, Kuo CH, Kuo PH, Chien CH, Wu CC, Chan DD, Tsai MK, Tsai SF, Yu CJ. Outbreak investigation in a COVID-19 designated hospital: The combination of phylogenetic analysis and field epidemiology study suggesting airborne transmission. *J Microbiol Immunol Infect* 2023; S1684-1182(23): 2–6.

106. Bivolarova M, Ondráček J, Melikov A, Ždímal V. A comparison between tracer gas and aerosol particles distribution indoors: The impact of ventilation rate, interaction of airflows, and presence of objects. *Indoor Air* 2017; 27(6): 1201–1212.

107. Sze To GN, Wan MP, Chao CY, Wei F, Yu SC, Kwan JK. A methodology for estimating airborne virus exposures in indoor environments using the spatial distribution of expiratory aerosols and virus viability characteristics. *Indoor Air* 2008; 18(5): 425–438.

108. Nielsen PV, Li Y, Buus M, Winther FV, Qian H. Cross infection in a hospital ward and deposition of particles exhaled from a source patient. In *BEPH* 2009.

109. Mousavi ES, Grosskopf KR. Directional Airflow and Ventilation in Hospitals: A Case Study of Secondary Airborne Infection. *Energy Procedia* 2015; 78: 1201–1206.

110. Lindsley WG, King WP, Thewlis RE, Reynolds JS, Panday K, Cao G, Szalajda JV. Dispersion and exposure to a cough-generated aerosol in a simulated medical examination room. *J Occup Environ Hyg* 2012; 9(12): 681–690.

111. Qian H, Li Y, Nielsen PV, Hyldgaard CE. Dispersion of exhalation pollutants in a two-bed hospital ward with a downward ventilation system. *Build Environ* 2008; 43(3): 344–354.

112. Qian H, Li Y, Nielsen PV, Hyldgaard CE, Wong TW, Chwang AT. Dispersion of exhaled droplet nuclei in a two-bed hospital ward with three different ventilation systems. Indoor Air 2006;16(2):111–28.

113. Yin Y, Gupta JK, Zhang X, Liu J, Chen Q. Distributions of respiratory contaminants from a patient with different postures and exhaling modes in a single-bed inpatient room. *Build Environ* 2011; 46(1): 75–81.

114. Eames I, Shoaib D, Klettner CA, Taban V. Movement of airborne contaminants in a hospital isolation room. *J R Soc Interface* 2009; 6(Suppl 6): S757–766.

115. Cadnum JL, Jencson AL, Memic S, Osborne AO, Torres-Teran MM, Wilson BM, Deshpande A, Donskey CJ. Real-World Evidence on the Effectiveness of Plexiglass Barriers in Reducing Aerosol Exposure. *Pathog Immun* 2022; 7(2): 66–77.

116. Grosskopf KR, Herstein KR. The aerodynamic behavior of respiratory aerosols within a general patient room. *HVAC&R Res* 2012; 18(4): 709–22.

117. Pertegal V, Lacasa E, Cañizares P, Rodrigo MA, Sáez C. Understanding the influence of the bioaerosol source on the distribution of airborne bacteria in hospital indoor air. *Environ Res* 2023; 216(Pt 1): 114458.

118. Hayden CS, Johnston OE, Hughes RT, Jensen PA. Air volume migration from negative pressure isolation rooms during entry/exit. *Appl Occup Environ Hyg* 1998; 13(7): 518–527.

119. Kalliomäki P, Saarinen P, Tang JW, Koskela H. Airflow patterns through single hinged and sliding doors in hospital isolation rooms - Effect of ventilation, flow differential and passage. *Build Environ* 2016; 107: 154–168.

120. Tang JW, Nicolle A, Pantelic J, Klettner CA, Su R, Kalliomaki P, Saarinen P, Koskela H, Reijula K, Mustakallio P, Cheong DK, Sekhar C, Tham KW. Different types of door-opening motions as contributing factors to containment failures in hospital isolation rooms. *PLoS One* 2013; 8(6): e66663.

121. Hathway A, Papakonstantis I, Bruce-Konuah A, Brevis W. Experimental and modelling investigations of air exchange and infection transfer due to hinged-door motion in office and hospital settings. *Int J Vent* 2015; 14(2): 127–140.

122. Bhattacharya A, Ghahramani A, Mousavi E. The effect of door opening on air-mixing in a positively pressurized room: Implications for operating room air management during the COVID outbreak. *J Build Eng* 2021; 44: 102900.

123. Kalliomäki P, Hagström K, Itkonen H, Grönvall I, Koskela H. Effectiveness of directional airflow in reducing containment failures in hospital isolation rooms generated by door opening. *Build Environ* 2019; 158: 83–93.

124. Pasquarella C, Balocco C, Colucci ME, Saccani E, Paroni S, Albertini L, Vitali P, Albertini R. The Influence of Surgical Staff Behavior on Air Quality in a Conventionally Ventilated Operating Theatre during a Simulated Arthroplasty: A Case Study at the University Hospital of Parma. *Int J Environ Res Public Health* 2020; 17(2): 452.

125. Annaqeeb MK, Zhang Y, Dziedzic JW, Xue K, Pedersen C, Stenstad LI, Novakovic V, Cao G. Influence of surgical team activity on airborne bacterial distribution in the operating room with a mixing ventilation system: a case study at St. Olavs Hospital. *J Hosp Infect* 2021; 116: 91–98.

126. de Souza SO, Cardoso AA Jr, Sarmento ASC, d'Errico F. Effectiveness of a UVC air disinfection system for the HVAC of an ICU. *Eur Phys J Plus* 2022; 137(1): 37.

127. Menzies D, Adhikari N, Arietta M, Loo V. Efficacy of environmental measures in reducing potentially infectious bioaerosols during sputum induction. *Infect Control Hosp Epidemiol* 2003; 24(7): 483–489.

128. Miller SL, MacHer JM. Evaluation of a methodology for quantifying the effect of room air ultraviolet germicidal irradiation on airborne bacteria. *Aerosol Sci Technol* 2000; 33(3): 274–295.

129. McDevitt JJ, Milton DK, Rudnick SN, First MW. Inactivation of poxviruses by upper-room UVC light in a simulated hospital room environment. *PLoS One* 2008; 3(9): e3186.

130. Chen YC, Liao CH, Shen WT, Su C, Wu YC, Tsai MH, Hsiao SS, Yu KP, Tseng CH. Effective disinfection of airborne microbial contamination in hospital wards using a zero-valent nano-silver/TiO_2 -chitosan composite. *Indoor Air* 2019; 29(3): 439–449.

131. Bennett DH, McKone TE, Evans JS, Nazaroff WW, Margni MD, Jolliet O, Smith KR. Defining intake fraction. *Environ Sci Technol* 2002; 36(9): 206A–211A.

132. Brohus H. Personal exposure to contaminant sources in ventilated rooms. 1997.

133. Riley EC, Murphy G, Riley RL. Airborne Spread of Measles in a Suburban elementary school. *Am J Epidemiol* 1978; 107(5): 421–432.

134. Sze To GN, Chao CY. Review and comparison between the Wells-Riley and dose-response approaches to risk assessment of infectious respiratory diseases. *Indoor Air* 2010; 20(1): 2–16.

135. Chao CYH, Wan MP, Morawska L, Johnson GR, Ristovski ZD, Hargreaves M, Hargreaves M, Mengersen K, Corbett S, Li Y, Xie X, Katoshevski D. Characterization of expiration air jets and droplet size distributions immediately at the mouth opening. *J Aerosol Sci* 2009; 40(2): 122–133.

136. Morawska LJ, Johnson GR, Ristovski ZD, Hargreaves M, Mengersen K, Corbett S, Chao CYH, Li Y, Katoshevski D. Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities. *J Aerosol Sci* 2009; 40(3): 256–269.

137. Ai Z, Mak CM, Gao N, Niu J. Tracer gas is a suitable surrogate of exhaled droplet nuclei for studying airborne transmission in the built environment. *Build Simul.* 2020; 13(3): 489–496.

138. Rudnick SN, Milton DK. Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. *Indoor Air* 2003; 13(3): 237–245.

139. Chojer H, Branco PTBS, Martins FG, Alvim-Ferraz MCM, Sousa SIV. Development of low-cost indoor air quality monitoring devices: Recent advancements. *Sci Total Environ* 2020; 727: 138385.

140. Tsang TW, Mui KW, Wong LT, Law KY, Shek KW. A Novel IoT-Enabled Wireless Sensor Grid for Spatial and Temporal Evaluation of Tracer Gas Dispersion. *Sensors* 2023; 23(8): 3920.

141. Peladarinos N, Cheimaras V, Piromalis D, Arvanitis KG, Papageorgas P, Monios N, Dogas I, Stojmenovic M, Tsaramirsis G. Early Warning Systems for COVID-19 Infections Based on Low-Cost Indoor Air-Quality Sensors and LPWANs. *Sensors (Basel)* 2021; 21(18): 6183.