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Review

Heating, ventilation, and air-conditioning systems in healthcare: a scoping review

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SUMMARY

Guidelines for heating, ventilation, and air-conditioning systems have been developed for different settings. However, there is a lack of up-to-date evidence providing concrete recommendations for the heating, ventilation, and air-conditioning systems of an isolation room, which is essential to appropriately guide infection control policies. To highlight the guidelines for heating, ventilation, and air-conditioning systems in isolation rooms to inform relevant stakeholders and policymakers. A systematic search was performed based on Joanna Briggs Methodology using five databases (CINAHL, Embase, Joanna Briggs Institute, Medline, and Web of Science) and websites. Eight articles published by government departments were included in this review. Most studies recommended controlled airflow without recirculation, 12 air changes per hour, high-efficiency particulate air filtrate to exhaust contaminated air from the airborne isolation room, humidity ≤60%, and temperature in the range of 18–30 °C. This review provides further evidence that there is a need for interdisciplinary collaborative research to quantify the optimum range for heating, ventilation, and air conditioning system parameters, considering door types, anterooms, and bed management, to effectively reduce the transmission of infection in isolation rooms.

Introduction

Human-to-human transmission of airborne infections can occur through the inhalation of expiratory aerosols in the short or long range [1]. Severe acute respiratory syndrome coronavirus (SARS-CoV) and Middle East respiratory syndrome coronavirus (MERS-CoV), identified in 2003 and 2012, respectively, are highly transmissible, causing mild-to-severe infections that threaten public health security [2]. Unfortunately, the coronavirus disease 2019 (COVID-19), discovered in 2019, poses a higher risk to healthcare professionals and other patients, as its transmission has been shown to be more severe than its predecessors [3]. According to the Centers for Disease Control and Prevention (CDC) COVID-19 Response Team, more than half of the 9282 healthcare professionals in the USA who tested positive for COVID-19 by April 2020 were exposed in their workplace [4]. Although patient care is expected to provide a safe environment under healthcare settings, these healthcare facilities may be vulnerable to the rapid spread of infectious

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agents [5]. Qian *et al.* identified 318 COVID-19 outbreaks and suggested that a shared indoor environment is a major source of infection [6].

Controlling airborne transmission requires infection control and interventions in healthcare facilities. Other than administrative controls (e.g. detection of infection and health education) and personal protection (e.g. wearing personal protective equipment (PPE) such as masks or respirators), environmental control is required to prevent the spread of the virus through the same breathing zone [7]. Given that controlling the movement of airborne particles depends on airflow, insufficient ventilation may cause these particles to remain in hospital rooms and consequently be inhaled by anyone entering [8]. To support a healthy healthcare environment, hospital rooms require well-designed heating, ventilation, and air-conditioning (HVAC) systems characterized by seven key elements, i.e. heating, cooling, humidifying, dehumidifying, cleaning, ventilating, and air movement [9].

According to Moscato *et al.*, HVAC systems provide a comfortable and safe environment for patients and serve as an eradicator of communicable diseases and viruses [10]. Therefore, carefully designed HVAC systems are crucial in healthcare facilities and for their operators and visitors because they can reduce the infection rates of airborne diseases, enhance indoor air quality, and protect healthcare professionals and patients [11]. To date, insufficient evidence exists for concrete recommendations on the design of HVAC systems in isolation rooms to address infectious pandemics or the development of nationwide guidelines for pandemic control and protection. Although Guo *et al.* conducted a review to compare the HVAC operation guidelines of several countries during the COVID-19 pandemic, it lacked methodological rigor (e.g. no specific protocol was used to guide the review, and the search and data extraction strategies were not exemplified), and it covered different settings (e.g. offices and buildings) instead of isolation rooms at hospitals [12]. Considering the detrimental effects of airborne infections, this review highlighted guidelines for HVAC systems in isolation rooms to inform relevant stakeholders and policymakers. This review aimed to highlight the guidelines for heating, ventilation, and air-conditioning systems in isolation rooms to inform relevant stakeholders and policymakers.

Methods

A scoping review was conducted based on Joanna Briggs Institute methodology [13]. The following question was used as a guideline: What are the similarities and differences among the guidelines of HVAC systems for airborne infection control worldwide?

Literature search

A systematic search of the literature from five databases (CINAHL, Embase, Joanna Briggs Institute, Medline, and Web of Science) was conducted. In addition, a manual search was performed to ensure that relevant available articles were retrieved, as some articles might have been missing from the databases [14]. A list of keywords and Medical Subject Headings including 'infection control OR isolation room' AND 'HVAC OR heating OR ventilation OR air conditioning' were used in the search (Supplementary Table S1).

Study inclusion and exclusion criteria

The inclusion criteria were (1) English and Chinese articles that reported standards and clinical practice guidelines and (2) published from 2012 onwards, as MERS-CoV was identified in 2012 and there were rapid innovations in medical technologies, where older guidelines (e.g. using guidelines from 2003 during the SARS outbreak) may not be useful to inform up-to-date practices [15]. Exclusion criteria were (1) non-guidelines and (2) short, non-peer-reviewed articles, such as commentaries and editorials.

Study selection and data extraction

Articles retrieved from the databases were imported into ProQuest Refworks, a reference management software [16]. Duplicate articles were removed using a tool provided by the software. Subsequently, the titles and abstracts of articles were screened independently by two reviewers. Data from relevant articles were extracted according to author, year, country, setting, temperature, relative humidity, source of air ventilation, airflow, exhaust air treatment, and air changes per hour (Table I) [17–24]. The first reviewer extracted the data into an Excel spreadsheet and the data were verified by a second reviewer. For discrepancies that occurred during data extraction, a third reviewer was consulted to reach consensus. According to Pollock *et al.*, methodological appraisals and risk-of-bias assessments are not mandatory for scoping reviews [25].

Data synthesis

The data extracted from the relevant articles were grouped together based on the key elements of the HVAC systems.

Results

Search results

A Preferred Reporting Items for Systematic Reviews and Meta-Analyses diagram was used to present the search and study selection (Figure 1). The comprehensive search resulted in 7120 articles from five electronic databases and seven articles from Google. A total of 1838 duplicates were removed from the databases, leaving 5282 articles for title and abstract screening. Six full-text articles from the databases were reviewed after removing articles with irrelevant titles and abstracts: 5139 and 137, respectively. None of the studies met the inclusion criteria. Finally, eight manually searched articles were included in the narrative synthesis.

Guideline characteristics

Three guidelines were published in Western countries, including the USA, England, and Australia, whereas the others were published in Asian countries, including the United Arab Emirates (Dubai), Southeast Asia (Singapore and Malaysia), South Asia (India), and East Asia (China). These articles were

Table I

Summary of the heating, ventilation, and air conditioning systems for negative pressure isolation room/COVID-19 patient room from different countries

Author (year)	Country	Setting	Temperature	Relative humidity	Airflows	Pressure gradient	Treatment of exhaust air	Air changes per hour (ACH)
Centers for Disease Control and Prevention (2019) [17]	USA	Airborne infection isolation room	24 °C	Not mentioned	Air flows from the corridors to the isolation room	Pressure differential of 2.5 Pa	Air exhausted directly to the outside if possible or HEPA-filtered if recirculated	≥6 ACH for existing facilities, ≥12 ACH for areas under renovation or for new construction
National Health Service (2021) [18]	England	Negative pressure isolation room	20–25 °C	≤60%	Supply air from corridor passing into room via door undercut, transfer grille or pressure stabilizer	Pressure regime: −5 Pa to general area	Extract filters will not be required provided extract fan can discharge in a safe location 3000 mm above the height of the building. If extract filters are fitted, should be of HEPA grade.	≥10 ACH
Australasian Health Infrastructure Alliance (2017) [19]	Australia	Negative pressure isolation room	Not mentioned	Not mentioned	Sealed room with barometric dampers for controlled air flow is required. 100% outside air ventilation	The minimum differential pressure between the isolation room and adjacent ambient pressure areas: −20 to −30 Pa (the isolation room has an anteroom), and −10 to −15 Pa (no anteroom).	Exhaust duct under negative pressure within building with duplex fans. HEPA filter is not a must for a negative pressure room but HEPA filter is recommended for Quarantine isolation – a Class N room including an anteroom and fumigation facilities.	≥10 ACH or 145 L per patient
Ministry of Health Singapore (2017) [20]	Singapore	Airborne isolation room	Not mentioned	Not mentioned	Inward directional airflow from adjacent spaces to the room. Non-recirculatory system.	Negative pressure differentials of >−2.5 Pa	All room exhaust air must be HEPA-filtered (at least H14 grade or equivalent)	≥12 ACH

(*continued on next page*)

Table I (*continued*)

Author (year)	Country	Setting	Temperature	Relative humidity	Airflows	Pressure gradient	Treatment of exhaust air	Air changes per hour (ACH)
Government of Dubai and Dubai Health Authority (2019) [21]	United Arab Emirates (Dubai)	Negative pressure isolation room	21–24 °C	<60%	Non-recirculatory system	Pressure of the air flow –2.5 to –10 Pa differential	Exhaust air grille should be placed over the patient head or at low level near the head. Air from negative pressure room must be HEPA-filtered.	≥12 ACH
Government of India, Central Public Works Department (2019) [22]	India	COVID-19 patient room	24–30 °C	40% and 70%	Non-recirculatory system	Minimum of –2.5, preferably more than –5 Pa	– HEPA filters shall be a minimum of H13 filter class or equivalent – Treatment of exhaust air by chemical disinfection is acceptable (1% sodium hypochlorite solution)	≥12 ACH
Ministry of Health Malaysia and University Malaya Medical Centre (2021) [23]	Malaysia	Airborne infection isolation room (AIIR)	22–26 °C	≥60%	100% outside air ventilation. Air movement must be from clean to less clean area. Non-recirculatory system.	Differential pressure between AIIR and adjoining areas is –2.5 Pa	The exhaust air must be filtered with minimum efficiencies of HEPA	≥12 ACH or 160 L per patient
National Health Commission of the People's Republic of China (2020) [24]	China	Negative pressure isolation room	Winter: 18–20 °C. Summer: 26–28 °C	Not mentioned	Sterilized area to semi-contaminated zone to contaminated zone	Pressure differentials: 5–15 Pa	Air supply and exhaust should be filtered with HEPA	≥12 ACH

HEPA, high-efficiency particulate air filtration.

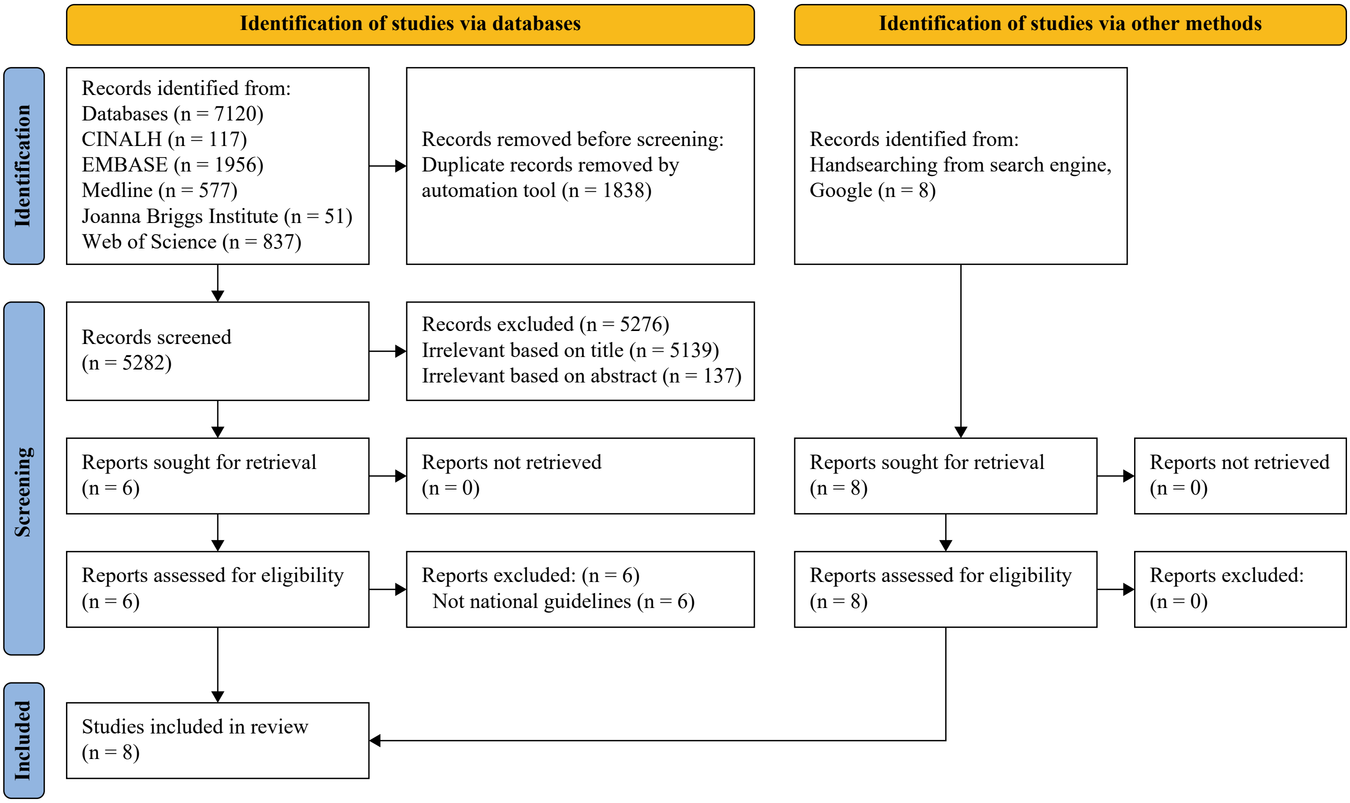

Figure 1. PRISMA 2020 flow diagram for study selection.

published between 2017 and 2021 by their respective government departments.

HVAC systems

Ventilation

The isolation room ventilation strategy is required to minimize the risk of airborne transmission. Air changes per hour (ACH) is defined as the rate of volumetric airflow divided by the dimensions of a room [26]. Under ideal conditions, the CDC estimated that when the ACH is 12, the required time to reach 99% and 99.5% removal efficiency is 23 and 35 min, respectively [27]. Generally, the guidelines suggest a minimum quantity of air supplied to the airborne infection isolation room, negative pressure isolation room, or COVID-19 patient room at a rate of 12 ACH [20–24]. NHS and Australasian Health Infrastructure Alliance guidelines recommend a minimum of 10 ACH, and the latter suggests that the air supplied should be $\geq$145 L per patient. For existing healthcare facilities, a minimum of 6 ACH is recommended [27].

Airflow

In healthcare facilities, airborne infection isolation rooms, negative pressure isolation rooms, and COVID-19 patient rooms are specifically designed to isolate individuals who are diagnosed with or suspected of being infected with an airborne infectious disease to prevent its spread. Considering that the risk of airborne infection can be reduced by optimal airflow within the built environment, controlling airflow patterns is important. The CDC and NHS recommend that air should flow from the corridors to the isolation room [17,18]. Similarly, guidelines from Malaysia, Singapore, and China also highlight that airflow movement should be in the inward direction, moving from clean areas to less clean areas [20,23,24]. Most recommendations (62.5%) suggest controlled airflow with no recirculation in the built environment [17,19,20,22,23].

The recommended minimum pressure gradient between the isolation room and adjacent spaces is −2.5 Pa [17,21–23]. The NHS suggests a higher differential pressure of 5 Pa between the negative-pressure isolation room and general area [18]. Nonetheless, the recommendations from Australia are higher than those stipulated in other guidelines, where the pressure gradient between the isolation room and adjacent spaces should be maintained between −20 and −30 Pa if there is an anteroom, and between −10 and −15 Pa if there is no anteroom [19]. According to Chinese guidelines, the recommended pressure differential between the isolation room and adjacent spaces should be in the range of 5–15 Pa [24].

Temperature

The key processes in HVAC systems include heating and cooling. The air in the built environment of healthcare facilities must be appropriately regulated by these two functions to achieve the target temperature. Based on the guidelines included in this scoping review, the recommended temperature of the airborne infection isolation room, negative-pressure isolation room, and COVID-19 patient room is between 18 and 30 °C. Specifically, the recommended temperature is 24 °C [17], 20–25 °C [18], 21–24 °C [21], 22–26 °C [23], and 24–30 °C [22]. The Chinese guidelines also state that the optimal temperature must be 18–20 °C in the winter and 26–28 °C in the summer [24]. Two articles did not specify any recommendations for temperature in the isolation room [20,19].

Relative humidity

A relative humidity level of ≤60% is recommended [18,21,23]. However, one guideline suggests a level between 40% and 70% [22]. Guidelines from the USA, Australia, and Singapore do not mention the required relative humidity levels for an isolation room.

Air biocontamination control

Decontamination of biological contaminants in critical air quality control environments, especially in healthcare facilities, may be performed using various methods. The guidelines suggest that high-efficiency particulate air (HEPA) filtration systems are optional [17—19]; however, four countries highlight the use of HEPA filters to exhaust contaminated air from airborne isolation rooms or negative pressure isolation rooms as a mandatory requirement [20,21,23,24]. Other decontamination methods in the guidelines include treating exhaust air with chemical disinfection, 1% sodium hypochlorite solution, and using an extraction fan to safely release contaminated air outside the building if air is not recirculated in the system [17,19,20].

Discussion

The findings of this scoping review indicated the similarities and differences in the operation of HVAC systems in different countries. During the initial stages of the COVID-19 outbreak, various researchers reported that the main route of COVID-19 transmission was via respiratory droplets. Recently, scientific evidence has suggests that its transmission is airborne [28]. COVID-19 is highly transmissible in poorly ventilated and closed environments, and Morawska and Milton highlighted the importance of providing effective ventilation with airborne infection controls [29]. A mechanical ventilation system was installed in a closed environment to suppress the transmission of infectious aerosols. To prevent the leakage of respiratory aerosols within an airborne infection isolation room, negative pressure must be maintained. According to the guidelines in this review, the pressure gradients should be maintained within 2.5—30 Pa. Similarly, Zhang *et al.* reported similar pressure gradient values in different countries [30]. In addition to maintaining pressure gradients within appropriate ranges, researchers have suggested using only fresh air and eliminating the recirculation of air within the ventilation system to minimize the spread of SAR-CoV-2 [31]. Chen *et al.* highlighted that there must be an association between the flow direction and pressure gradient from clean to semi-polluted, and finally to the polluted zone [32]. This is echoed by the guidelines of this review, which suggest that air moves inward from the cleanest to the least clean areas.

The fresh-air intake and indoor exhaust of a negative-pressure isolation room are closely related to the negative pressure difference and air exchange per hour [33]. Maintaining a minimum fresh airflow rate of 6—12 ACH in isolation rooms has been recommended. The exposure intensity and duration of remaining respiratory aerosols are reduced by higher ventilation (6—12 ACH) and filtration rates [34]. Although ventilation rates between 6 and 12 ACH are effective in diluting air in isolation rooms, negative pressure helps to prevent air leakage between the isolation room and adjacent areas. Opening doors and walking through doorways may be reasons for containment failures [35]. Considering the minimization of air exchange across the doorway, Kalliomaki *et al.* reported that sliding doors are better than hinged doors [35]. In addition to emphasizing HVAC systems, various factors need to be explored further to design isolation rooms that effectively remove contagious respiratory aerosols.

Although this current review focused on an isolation room only, the recommended temperature varies between 18 and 30 °C. Regarding the relative humidity of an isolation room, there are inconsistencies in the recommendations, with some variations between ≤60% and 40—70% among the guidelines in this review. Elsaid and Ahmed suggested that an adjustment to the air temperature and humidity levels in an air conditioning system of ≥30 °C and 80%, respectively, may limit COVID-19 transmission [36]. Unfortunately, in actual situations, the aforementioned parameters are deemed uncomfortable for individuals, and a high humidity may promote bacterial growth. During the COVID-19 pandemic, all healthcare professionals must wear full PPE when entering the airborne infection isolation room, negative pressure isolation room, and COVID-19 patient room, the majority of whom report thermal discomfort with being hot (69.1%) and uncomfortably humid (45.77%) [37]. Weng and Kau mentioned that the indoor temperature of negative pressure isolation rooms should be lower yet not <22 °C to provide comfort to both healthcare professionals and patients [33]. Aganovic *et al.* used a modified Wells—Riley model to estimate the effect of relative humidity on SAR-CoV-2 transmission in an indoor environment [38]. For the same small infectious droplet size range, a change in relative humidity from 37% to 53% demonstrated a marginal effect on the mean infection rate (reduced by ≤7%) when the ventilation rate was set at ACH 0.5. A greater reduction in the mean infection rate (54%) occurred at a ventilation rate of 6ACH with constant relative humidity. This further implied that ventilation rate plays a superior role to relative humidity in removing airborne SARS-CoV-2. Furthermore, Weng and Kau emphasized that the priority of negative pressure isolation rooms is to improve indoor air quality and minimize air cross-infection [33]. Therefore, the heating and cooling parameters in HVAC systems should be automatically regulated based on actual scenarios with acceptable temperatures and relative humidity for the comfort of occupants in an indoor environment [39].

For HVAC systems, air biocontamination control using HEPA filters has been recommended by most guidelines. HEPA filters are an important additional safety measure to clean the air from isolation rooms and protect the individuals around the rooms [40,41]. This is also supported by the CDC as a strategy to protect healthcare professionals and non-infected patients from those infected if the air is recirculated [27]. Johnson *et al.* revealed a positive effect of the HEPA-filtered fan unit on the containment efficiency for isolation configurations, demonstrating that the efficiencies exceeded 99.7% for all conditions, with or without an anteroom, and with simulated provider traffic [42]. In addition, having a HEPA machine in an isolation room was more cost-effective than the annual cost incurred for manual disinfection, as the cost:benefit ratio was 2.08 [43]. The containment efficiency and cost benefits may explain the use of HEPA filters in isolation rooms. An important aspect of HEPA filters is that they require regular maintenance and monitoring of its filtration efficiency to determine an appropriate replacement time [44]. Regardless of the evidence suggesting low hazards posed by HEPA filters, the maintenance, replacement, and safe disposal of used HEPA filters should be conducted by competent personnel following standard operating procedures and a suitable risk assessment owing to the potential contamination of pathogenic micro-organisms [45,46]. According to the NHS, it is not necessary to have extraction filters if an extraction fan can safely discharge contaminants 3 m above the building height [18]. The CDC stated that inhalation of the virus in the air at distances >6 feet (1.83 m) may cause the transmission of SARS-CoV-2, although the likelihood is low [27]. However, to the best of our knowledge, there is no published literature on the farthest distance of SARS-CoV-2 transmission through inhalation of the virus in air that exceeds 3 m. This may explain why some guidelines do not emphasize the mandatory use of HEPA filters. Only guidelines from India state that chemical disinfectants (1% sodium hypochlorite) are acceptable for the treatment of exhaust air from patients with COVID-19. According to this recommendation, chemical disinfection can be performed by bubbling exhaust air from a COVID-19 patient room by introducing the air into a 1% sodium hypochlorite solution [22]. Although sodium hypochlorite is one of the key ingredients in activating virucidal activity, its use in air biocontamination control is controversial, as it can cause detrimental health effects such as acute respiratory distress syndrome, rhabdomyolysis, haemolysis, and acute kidney injury [47,48]. Further research is required to explore the advantages and disadvantages of using this chemical disinfectant for air cleaning during the COVID-19 pandemic.

This study had several limitations. All articles were conducted in accordance with the clinical guidelines. The absence of randomized controlled trials prevented a causal interpretation of the impact of HVAC on patient outcomes. We conducted a literature search of the available guidelines in English and Chinese only and excluded other languages; thus, relevant guidelines in other countries using different languages might have been overlooked. However, this decision was made mainly because of lack of familiarity with authors in other languages and potential inaccuracy in data extraction. Future reviews should include international collaborations to explore guidelines in other languages.

This study reviews the HVAC system guidelines from several countries on different continents. Overall, the guidelines were consistent with each other, except for some minor differences in the parameters. In summary, ventilation, airflow, and air biocontamination control play an important role in isolation efficacy. Relative humidity has a marginal effect on limiting COVID-19 transmission in negative-pressure isolation rooms, and the temperature is set to a range that provides a comfortable environment for both healthcare professionals and patients instead of being actively involved in minimizing or eliminating the contaminants. Notably, other factors that are not related to HVAC systems, such as door type, anteroom, and bed management, must be considered when designing an isolation room to effectively reduce the transmission of infectious diseases.

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Author contributions

S.Y. Chair: conceptualization, writing — original draft, review and editing. S. T. Ng, C.Y.H. Chao, J.F. Xu: writing — review and editing.

Conflict of interest statement

None declared.

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Appendix A. Supplementary data

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References

[1] Li Y. Basic routes of transmission of respiratory pathogens — a new proposal for transmission categorization based on respiratory spray, inhalation, and touch. Indoor Air 2021;31:3–6.
[2] Al-Tawfiq JA, Zumla A, Memish ZA. Coronaviruses: severe acute respiratory syndrome coronavirus and Middle East respiratory syndrome coronavirus in travelers. Curr Opin Infect Dis 2014;27:411–7.
[3] Paules CI, Marston HD, Fauci AS. Coronavirus infections — more than just the common cold. JAMA 2020;323:707–8.
[4] Centers for Disease Control and Prevention (CDC) COVID-19 Response Team. Characteristics of health care personnel with COVID-19 — United States, February 12 — April 9, 2020. Morb Mortal Wkly Rep 2020;69:477–81.
[5] Sood G, Perl TM. Outbreaks in health care settings. Infect Dis Clin North Am 2016;30:661–87.
[6] Qian H, Miao T, Liu L, Zheng X, Luo D, Li Y. Indoor transmission of SARS-CoV-2. medRχiv; 2020.
[7] Aliabadi AA, Rogak SN, Bartlett KH, Green SI. Preventing airborne disease transmission: review of methods for ventilation design in health care facilities. Adv Prev Med 2011;2011:124064.
[8] Ather B, Mirza TM, Edemekong PF. Airborne precautions. Treasure Island. FL: StatPearls Publishing; 2022. Available at: https://www.ncbi.nlm.nih.gov/books/NBK531468/ [last accessed September 2023].
[9] McDowall R, editor. Fundamentals of HVAC systems. 1st edn. Atlanta: Elsevier; 2006.
[10] Moscato U, Borghini A, Teleman AA. HVAC management in health facilities. In: Capolongo S, Settimo G, Gola M, editors. Indoor air quality in healthcare facilities. Berlin: Springer; 2017. p. 95–106.
[11] Shajahan A, Culp CH, Williamson B. Effects of indoor environmental parameters related to building heating, ventilation, and air conditioning systems on patients' medical outcomes: a review of scientific research on hospital buildings. Indoor Air 2019;29:161–76.
[12] Guo M, Xu P, Xiao T, He R, Dai M, Miller SL. Review and comparison of HVAC operation guidelines in different countries during the COVID-19 pandemic. Build Environ 2021;187:107368.
[13] Peters MDJ, Godfrey C, McInerney P, Munn Z, Tricco AC, Khalil H. Scoping reviews. In: Aromataris E, Munn Z, editors. JBI manual for evidence synthesis. Joanna Briggs Institute; 2020. ch. 11.
[14] Hopewell S, Clarke MJ, Lefebvre C, Scherer RW. Handsearching versus electronic searching to identify reports of randomized trials. Cochrane Database Syst Rev; 2007. p. MR000001.
[15] Omrani AS, Shalhoub S. Middle East respiratory syndrome coronavirus (MERS-CoV): what lessons can we learn? J Hosp Infect 2015;91:188–96.

[16] Ivey C, Crum J. Choosing the right citation management tool: Endnote, Mendeley, Refworks, or Zotero. J Med Libr Assoc 2018;106:399–403.
[17] Centers for Disease Control and Prevention. Background C. air: guidelines for environmental infection control in health-care facilities. 2003. Available at: https://www.cdc.gov/infectioncontrol/guidelines/environmental/background/air.html/ [last accessed June 2023].
[18] National Health Service (NHS). Health Technical Memorandum 03-01 specialised ventilation for healthcare premises. Part A: the concept, design, specification, installation and acceptance testing of healthcare ventilation systems. 2021. Available at: https://www.england.nhs.uk/publication/specialised-ventilation-for-healthcare-buildings/ [last accessed January 2023].
[19] Australasian Health Infrastructure Alliance. Australasian health facility guidelines: isolation rooms – engineering and design requirements. 2017. Available at: https://healthfacilityguidelines.com.au/news/isolation-rooms-engineering-and-design-requirements/ [last accessed January 2023].
[20] Ministry of Health – Singapore. The national prevention and control guidelines for acute healthcare facilities. 2017. Available at: https://www.moh.gov.sg/hpp/all-healthcare-professionals/guidelines/GuidelineDetails/infection-prevention-and-control-guidelines-and-standards/ [last accessed January 2023].
[21] Government of Dubai and Dubai Health Authority. DHA health facility guidelines. Part E – engineering services; 2. Mechanical (HVAC) engineering design. 2019. Available at: https://www.dha.gov.ae/ [last accessed January 2023].
[22] Government of India, Central Public Works Department. COVID-19: guidelines for air conditioning and ventilation 2019. Available at: https://ishrae.in/ [last accessed January 2023].
[23] Ministry of Health Malaysia, University Malaya Medical Centre. Guidelines on ventilation in the healthcare setting to reduce the transmission of respiratory pathogens. 1st ed. 2021.
[24] National Health Commission of the People's Republic of China. Technical guidelines for the construction of negative pressure wards in emergency medical facilities for novel coronavirus pneumonia 2020. http://www.nhc.gov.cn/xcs/zhengcwj/202002/f6a6da92bfd649b699464b54591d68db.shtml/ [last accessed January 2023].
[25] Pollock D, Davies EL, Peters MDJ, Tricco AC, Alexander L, McInerney P, et al. Undertaking a scoping review: a practical guide for nursing and midwifery students, clinicians, researchers, and academics. J Adv Nurs 2021;77:2102–13.
[26] Zhang Y, Cao G, Feng G, Xue K, Pedersen C, Mathisen HM, et al. The impact of air change rate on the air quality of surgical microenvironment in an operating room with mixing ventilation. J Build Engng 2020;32:101770.
[27] Centers for Disease Control and Prevention (CDC). Guidelines for environmental infection control in health-care facilities. 2019. Available at: https://www.cdc.gov/infectioncontrol/guidelines/environmental/appendix/air.html/ [last accessed January 2023].
[28] Greenhalgh T, Jimenez JL, Prather KA, Tufekci Z, Fisman D, Schooley R. Ten scientific reasons in support of airborne transmission of SARS-CoV-2. Lancet 2021;397:1603–5.
[29] Morawska L, Milton DK. It is time to address airborne transmission of coronavirus disease 2019 (COVID-19). Clin Infect Dis 2020;71:2311–3.
[30] Zhang Y, Han O, Li A, Hou L, Olofsson T, Zhang L, et al. Adaptive wall-based attachment ventilation: a comparative study on its effectiveness in airborne infection isolation rooms with negative pressure. Engineering (Beijing) 2022;8:130–7.
[31] Morawska L, Tang JW, Bahnfleth W, Bluyssen PM, Boerstra A, Buonanno G, et al. How can airborne transmission of COVID-19 indoors be minimised? Environ Int 2020;142:105832.
[32] Chen Y, Lei J, Li J, Zhang Z, Yu Z, Du C. Design characteristics on the indoor and outdoor air environments of the COVID-19 emergency hospital. J Build Engng 2022;45:103246.
[33] Weng CL, Kau LJ. Planning and design of a full-outer-air-intake natural air-conditioning system for medical negative pressure isolation wards. J Healthc Engng 2021;2021:8872167.
[34] Allen JG, Ibrahim AM. Indoor air changes and potential implications for SARS-CoV-2 transmission. JAMA 2021;325:2112–3.
[35] 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;107:154–68.
[36] Elsaid AM, Ahmed MS. Indoor air quality strategies for air-conditioning and ventilation systems with the spread of the global coronavirus (COVID-19) epidemic: Improvements and recommendations. Environ Res 2021;199:111314.
[37] Zhu Y, Qiao S, Wu W, Li Y, Jian H, Lin S, et al. Thermal discomfort caused by personal protective equipment in healthcare workers during the delta COVID-19 pandemic in Guangzhou, China: a case study. Case Stud Therm Engng 2022;34:101971.
[38] Aganovic A, Bi Y, Cao G, Drangsholt F, Kurnitski J, Wargocki P. Estimating the impact of indoor relative humidity on SARS-CoV-2 airborne transmission risk using a new modification of the Wells–Riley model. Build Environ 2021;205:108278.
[39] Pan Y, Du C, Fu Z, Fu M. Re-thinking of engineering operation solutions to HVAC systems under the emerging COVID-19 pandemic. J Build Engng 2021;43:102889.
[40] Fusco FM, Schilling S, De Iaco G, Brodt HR, Brouqui P, Maltezou HC, et al. Infection control management of patients with suspected highly infectious diseases in emergency departments: data from a survey in 41 facilities in 14 European countries. BMC Infect Dis 2012;12:27.
[41] Lee JY. Tuberculosis infection control in health-care facilities: environmental control and personal protection. Tuberc Respir Dis (Seoul) 2016;79:234–40.
[42] Johnson DL, Lynch RA, Mead KR. Containment effectiveness of expedient patient isolation units. Am J Infect Control 2009;37:94–100.
[43] Bustarde J, Cruz JM, Dayap KK, De Leon KM, Cunanan-Yabut Jr A, Poso F, et al. Negative air pressure isolation room for COVID-19 patients in the Philippines: a simulation of the proposed design using SolidWorks. In: 2021 IEEE 13th international conference on humanoid, nanotechnology, information technology, communication and control, environment, and management (HNICEM). Manila: Institute of Electrical and Electronics Engineers; 2021. p. 1–6.
[44] Styczynski J, Tridello G, Donnelly JP, Iacobelli S, Hoek J, Mikulska M, et al. Protective environment for hematopoietic cell transplant (HSCT) recipients: The Infectious Diseases Working Party EBMT analysis of global recommendations on health-care facilities. Bone Marrow Transplant 2018;53:1131–8.
[45] Mittal H, Parks SR, Pottage T, Walker JT, Bennett AM. Survival of microorganisms on HEPA filters. Appl Biosaf 2011;16:163–6.
[46] NHS. Application of HEPA filter devices for air cleaning in healthcare spaces: guidance and standards 2023. Available at: https://www.england.nhs.uk/long-read/application-of-hepa-filter-devices-for-air-cleaning-in-healthcare-spaces-guidance-and-standards/ [last accessed June 2023].
[47] Pradhan D, Biswasroy P, Kumar Naik PK, Ghosh G, Rath G. A review of current interventions for COVID-19 prevention. Arch Med Res 2020;51:363–74.
[48] Chatterjee A. Use of hypochlorite solution as disinfectant during COVID-19 outbreak in India: from the perspective of human health and atmospheric chemistry. Aerosol Air Qual Res 2020;20:1516–9.