Infection Control Guide on Heating, Ventilation and Air Conditioning (HVAC)

for Health Care Facilities Managers

PROJECT FIRSTLINE
CDC'S National Training Collaborative for Healthcare Infection Prevention & Control

ASHE
Optimizing health care facilities

Acknowledgements

- American National Standards Institute (ANSI)
- Centers for Disease Control and Prevention (CDC)
- The Facility Guidelines Institute (FGI)
- American Society for Health Care Engineering (ASHE)
- American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)

Produced by

- TLC Engineering Solutions
    - Michael P. Sheerin, PE, LEED AP
    - Robert D. Danner
    - Kim E Shinn, PE, LEED Fellow, BEMP
    - Aaron L. Johnson, PE, LEED AP BD + C
    - Anthony A. Scaccia PE, LEED AP BD + C

Table of Contents

Table of Contents 2
Introduction 3
Brief Review of Resources 5
In-Depth Resource Review 7
Ventilation 7
Filtration 7
HVAC Equipment 9
Pressurization 11
Dilution 13
Airborne Infection Isolation Rooms (AIIRs) 14
Protective Environment (PE) Rooms 15
Other Factors 15
Best Practices and Recommendations 16
Communication 16
System Upgrades 17
Maintenance 18
Relative Humidity 19
Pressure Monitors 20
Anterooms 21
Personal Protective Equipment 22
New and Emerging Technology 22
Conclusion 23
Case Studies 24
Case Study A: FGI 2021 24
Case Study B: Shobha Subhash 2013 25
Case Study C: Health Care Facility in Southeastern US 2020 25
Tools 27
Glossary 28
Endnotes 30

Introduction

Just as nurses and doctors are responsible for the patient's health and wellness, the health care facilities team is responsible for the building's health and wellness. A building not operating as intended can significantly affect all occupants.

A heating, ventilation and air-conditioning (HVAC) system is an integral part of a hospital's infection control protocols. The HVAC system is responsible for tempering the air, adjusting the relative humidity in a space, establishing pressurization relationships between spaces, filtering and diluting the air recirculated through the building, ventilating the building and flushing contaminants from spaces.[1] This document will explore each of these concepts as they relate to infection control.

Depending on the facility type, a HVAC designer will typically prescribe parameters as defined by the American National Standards Institute (ANSI), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the American Society for Health Care Engineering (ASHE) in ANSI/ASHRAE/ASHE Standard 170, *Ventilation of Health Care Facilities* and/or ANSI/ASHRAE Standard 62.1, *Ventilation for Acceptable Indoor Air Quality*.[2]

During the HVAC design process, which should include the facilities management team, appropriate air quantities (quantity of air flowing through a space) will be calculated to meet cooling and heating conditions and adhere to minimum required air changes per hour (ACH).[3] Air changes refer to continuous airflow through a space to dilute contaminant levels.

The team will also establish the filtration level necessary to remove contaminants from the airstream and clean the air for recirculation.[4] Air that is stale and air that is dirty is exhausted via relief air vents and discharged to the outdoors to balance air quantities from the economizer, which uses cool outdoor air instead of air conditioning, as applicable. It is important to note that exhausted air must be replaced by conditioned outdoor air, not air from the economizer. Unconditioned outdoor migrating into the building may result in temperature and humidity control issues along with unfiltered contaminants and the possible development of microbiological growth, especially where humid conditions occur.[5] Microbrial growth can lead to unsafe air for building occupants and unsafe conditions for patients.

Figure 1 provides a basic ventilation schematic. Fresh outside air (OSA) is taken into the system by a louvered connection in the building skin designed to protect the building from weather (blue ductwork in Figure 1) and taken to a central station air-handling unit (AHU), which conditions and filters the air. Then the air passes through a fan and becomes supply air to ventilate spaces (green ductwork). After ventilating a space, the air is either recirculated to the AHU (yellow ductwork) to be mixed with outdoor air or reconditioned (i.e., filtered, heated/cooled, humidified as applicable) and resupplied to a space, or exhausted by a fan (red

ductwork) and discharged from the building.

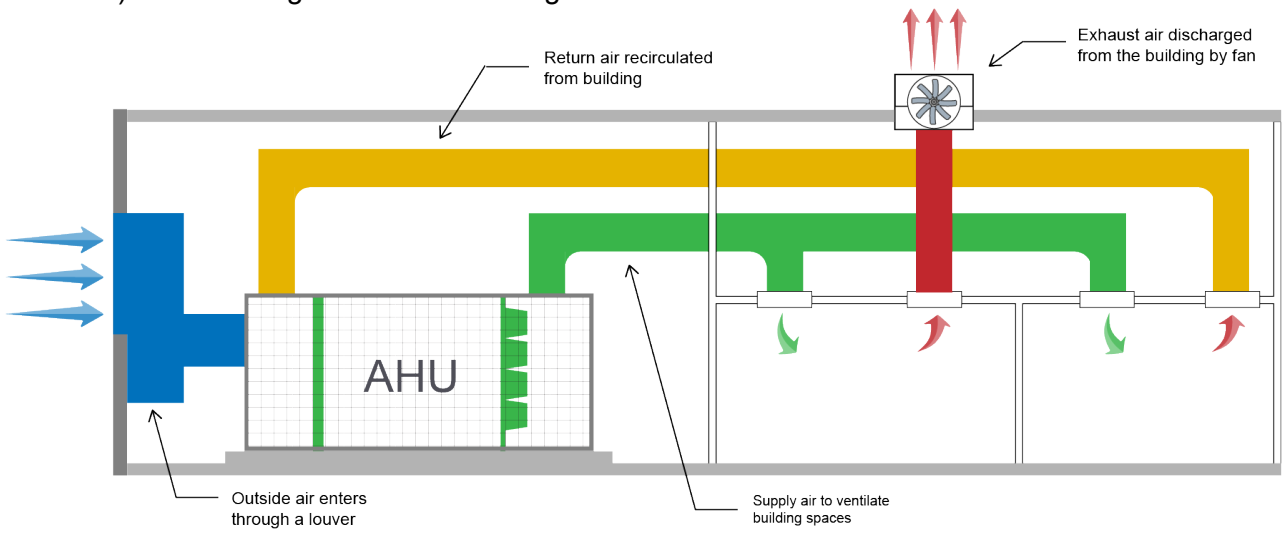

Figure 1. Ventilation system schematic.

The first principle of an HVAC system's role in infection control is the control of contaminants, substances such as bacteria, viruses and fungus that make the air impure and hazardous to breathe.[6] This is accomplished with dilution of contaminant levels by air changes, removal of contaminants (preferably at their source) by filtering delivered air and exhausting air as appropriate, and air balancing to create air pressure differentials that move the air from clean to less clean areas.[7] When the need arises and/or if direction is unclear, you should adhere to these containment control strategies.

Brief Review of Resources

A building's heating, ventilation and air-conditioning (HVAC) design is driven by facility type as well as location, climate, building codes and available capital. Many organizations provide guides, guidelines or requirements for HVAC system design and sizing. While local and state code references and adoptions may vary from location to location, the most pertinent guides or codes come from the following organizations and standards. This section details these resources.

- The Facility Guidelines Institute (FGI)
- ANSI/ASHRAE/ASHE Standard 170, *Ventilation of Health Care Facilities*
- ANSI/ASHRAE Standard 52.2, *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*
- ANSI/ASHRAE Standard 62.1, *Ventilation for Acceptable Indoor Air Quality*
- The Centers for Medicare & Medicaid Services (CMS)
- The Joint Commission (TJC)

FGI establishes guidelines dedicated to the planning, design and construction of hospitals, outpatient facilities, and residential health, care and support facilities. These guidelines are extensive and address health care considerations such as safety and infection control risk assessments, minimum dimensional requirements, and support space requirements for particular space types throughout a facility.[8] There are distinct editions of the FGI *Guidelines* for each health care facility type, and each one references or integrates ANSI/ASHRAE/ASHE Standard 170.[9] The FGI *Guidelines* are updated every four years and are typically adopted through state health care regulations and applied by TJC as adopted by or in the absence of state requirements.[10]

ANSI/ASHRAE/ASHE Standard 170 dictates the minimum HVAC requirements of health care facilities. As a continuous maintenance standard, changes published as "addenda" can be issued to it at any time. Periodic republication incorporating these changes occurs in alignment with the FGI *Guidelines*. Design temperatures and relative humidity ranges, air changes per hour (ACH), filtration requirements, pressure relationships and exhaust requirements are specified here, along with room-specific and infrastructure-level requirements.[11]

ANSI/ASHRAE Standard 52.2 establishes minimum efficiency reporting value (MERV) ratings for filters, which indicate how many particles filters absorb from the air. Based on the capture rate of particles at various sizes, the filters receive a MERV rating that allows consumers to compare products on a uniform scale.[12]

ANSI/ASHRAE Standard 62.1 defines the quality and quantity of outside air brought into a building to ventilate each space.[13] While it does not address health care spaces specifically, ANSI/ASHRAE Standard 62.1 does address outdoor air requirements for non-health care spaces in a health care facility and provides important guidance related to air quality and filtration in certain climatic zones, such as areas with high particulate or ozone conditions.[14] As a continuous maintenance standard, addenda can be issued to it at any time. Republication incorporating these changes occurs periodically.[15] Common applications for non-health care spaces include outdoor air quantities dictated by usage type, floor area and the maximum

amount of people that will occupy the space. There are also exhaust requirements for some spaces where the amount of exhaust required is quantified by their area.[16]

CMS, which is part of the U.S. Department of Health and Human Services, has a critical role within health care regulatory compliance as a major authority having jurisdiction (AHJ). CMS sets standards (Conditions of Participation [CoPs]) for hospital certification. CMS certification is not mandatory, but without it a hospital is unable to receive reimbursement from Medicare and Medicaid.[17] At the time of writing, CMS adopts the National Fire Protection Association (NFPA) 99, *Health Care Facilities Code*, 2012 edition, under which ANSI/ASHRAE/ASHE Standard 170, 2008 edition, is enforced.[18] For the latest code adoption updates, consult cms.org and ashe.org.

TJC is an independent nonprofit organization that health care facilities voluntarily enroll with as their accrediting organization. Hospitals are typically accredited during a three-year cycle and laboratories, every two years.[19] TJC's elements of performance (EPs) are based on or exceed CMS standards. TJC surveyors evaluate accreditation eligibility and status with on-site inspections of health care facilities. Among other things, a TJC survey assesses Environment of Care (EoC) items, which include HVAC system and space parameters.

In-Depth Resource Review

Material most relevant to infection control from the resources described in the previous section is elaborated upon here. Most jurisdictions have adopted the following material as code.

Ventilation

Ventilation refers to a process where fresh outside air (OSA) is brought into a building. The HVAC system moves the following types of air around the building: OSA, supply air, return air and exhaust air.

- **Fresh OSA** is brought in to establish pressure relationships and dilute recirculated return air from the building.
- **Supply air** has been conditioned by HVAC equipment and is used to ventilate and temper building spaces. Air is then recirculated to the HVAC equipment as **return air** to be filtered, mixed and diluted with fresh OSA before being conditioned and supplied again.
- Some space types (e.g., restrooms, airborne infection isolation rooms [AIIRs], kitchens, etc.) generate air too dirty for reuse, which instead is exhausted out of the building with a fan (**exhaust air**).[20]

As previously mentioned, the amount of outside air delivered to a space is determined by ANSI/ASHRAE Standard 62.1, *Ventilation for Acceptable Indoor Air Quality* [21] or by ANSI/ASHRAE/ASHE Standard 170, *Ventilation of Health Care Facilities* for health care spaces specifically.[22] ANSI/ASHRAE Standard 62.1 uses space type, occupancy and floor area to determine the quantity of outside air delivered to a space.[23] ANSI/ASHRAE/ASHE Standard 170 also considers space type but specifies the air changes per hour (ACHs) as well.[24] An HVAC designer will design non-health care spaces to ASHRAE Standard 62.1 minimum requirements and a health care space to whichever requirement is more stringent between ANSI/ASHRAE Standard 62.1 and ANSI/ASHRAE/ASHE Standard 170.

Filtration

Filtration and dilution are important functions of an HVAC system. Without proper filtration, building occupants could be delivered air burdened with environmental irritants and contaminants, and the HVAC equipment could be damaged over time by the buildup of dust and contaminants that can clog coils and restrict airflow.[25]

Air filters are pleated fiber media that catch particles from air passing through them with varying levels of effectiveness. Filters are rated on a minimum efficiency reporting value (MERV) system based on the filter's ability to catch particles of different sizes. Table 1, taken from ASHRAE Standard 52.2, *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*, shows the filtration efficiency required to attain different MERV ratings, or to be classified as a high efficiency particulate air (HEPA) filter.[26] A typical

commercial building will have a MERV 8,[27] while a typical inpatient space will have at least a MERV 14 for patient care spaces.[28]

Particle sizes are the dimensions of the individual solid, liquid or gaseous particles in question. Particle size is measured in microns (μ), and one micron is defined as one micrometer, or a one millionth of a meter.[29] For reference, a human hair is approximately 70 microns in diameter and a piece of paper is 100 microns.[30] From an infection control perspective, particle sizes may be in the range of 0.1 microns for SARS-CoV-2 or 0.015-0.030 microns for the cold virus (rhinovirus).

MERV rating	Average particle size efficiency (PSE) 0.3-1.0 microns	Average particle size efficiency (PSE) 1.0-3.0 microns	Average particle size efficiency (PSE) 3.0-10.0 microns
1			< 20%
2			< 20%
3			< 20%
4			< 20%
5			20-34.9%
6			35-49.9%
7			50-69.9%
8			70-84.9%
9		< 50%	≥ 85%
10		50-64.9%	≥ 85%
11		65-79.9%	≥ 85%
12		80-89.9%	≥ 90%
13	< 70%	≥ 90%	≥ 90%
14	75-84.9%	≥ 90%	≥ 90%
15	85-94.9%	≥ 90%	≥ 90%
16	≥ 95%	≥ 95%	≥ 95%
HEPA	≥ 99.97%	≥ 99.97%	≥ 99.97%

Table 1. Filtration level by MERV rating. Source: ASHRAE Standard 52.2.

HEPA filters are so effective that HEPA-filtered air is cleaner and has less particulate than fresh OSA. HEPA filters were designed to filter radioactive particles from the air by the U.S. Army during its development of nuclear weapons in World War II. These filters are still used in the nuclear power industry today[31] and similarly applied in pharmacy hoods.[32] Other special, yet familiar, applications where HEPA filters may be found in a health care setting include the ceiling supply diffusers of orthopedic or neurosurgical operating rooms.[33] It should be noted that high-level filtration requires the higher fan power to pull and blow across the advanced filtration and will result in increased energy use. If the fans do not have available power to pull across the upgraded filters, downstream pressure relationships or ACHs could be impacted. Additionally, HEPA filters should be challenge tested upon installation to confirm that the special seals that minimize air bypass and the filter media are functioning as planned.

HVAC Equipment

HVAC equipment that is conditioning air (e.g., AHUs, fan coil units [FCUs], etc.) will generally have two filters or one. A two-filter arrangement is shown in Figure 2, and a single-filter arrangement in Figure 3. Larger equipment such as central station AHUs will typically be equipped with a pre-filter to protect the AHU internal components, and separate final filters. Final filters are more robust than pre-filters and remove contaminants from the air before delivery to the occupied spaces.[34]

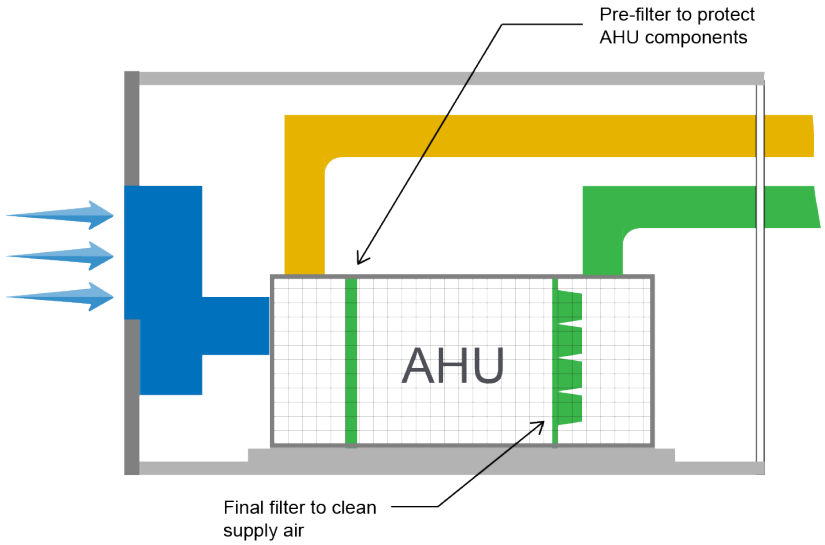

Figure 2. Pre-filter and final filter locations.

Smaller equipment such as fan coils likely have only a single filter, which will provide limited (if any) contaminant filtration of the air. These pre-filters are likely only MERV 8 rated and will not provide high levels of infection control.[35] Spaces requiring infection control measures such as filtration, dilution, humidification or pressurization may necessitate central station AHUs or other HVAC equipment. In-room recirculating units (e.g., FCUs, air conditioners or heat pumps) also do not have high filtration requirements and should be used for cooling and heating only, unless the units are specially built and equipped to achieve higher-level filtration and/or environmental conditioning parameters.

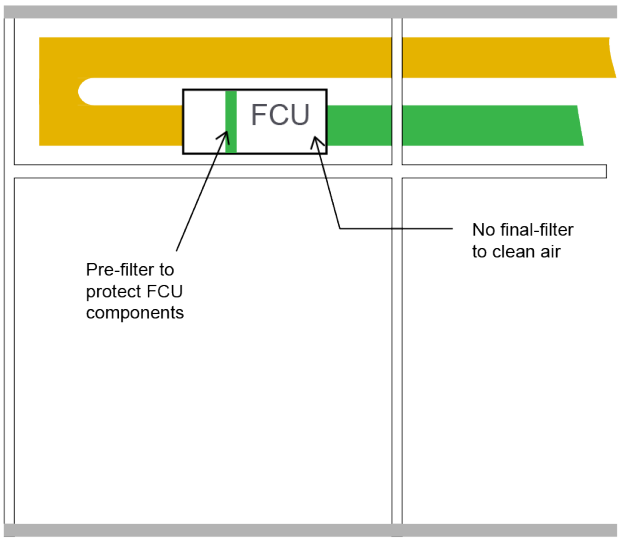

Figure 3. Fan coil unit filter.

For some spaces, ANSI/ASHRAE/ASHE Standard 170 requires specific locations for the supply air inlet and/or return/exhaust outlet. For example, in AIIR rooms the exhaust outlet should be located directly above the head of the bed as shown in Figure 4.[36] In this arrangement, the plume for an infectious patient's coughing, sneezing, etc., will be directed away from health care staff[37] into the exhaust grille and discharged directly outside of the hospital.[38]

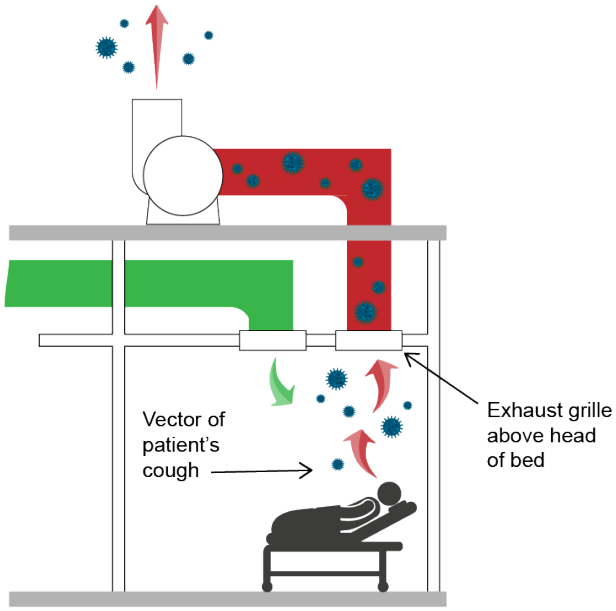

Figure 4. AIIR exhaust grille location.

Spaces such as operating rooms (ORs), bronchoscopy, certain nuclear imaging, and medical gas storage are designed with returns located low on the wall.[39] As shown in Figure 5, the purpose of these low wall returns is to either exhaust denser gas from the lower area of the room, or aid in creating an even (laminar) flow of air across a patient bed and away from health

care staff.[40] These low wall exhaust or return points must be kept clear of any equipment or materials to function properly.

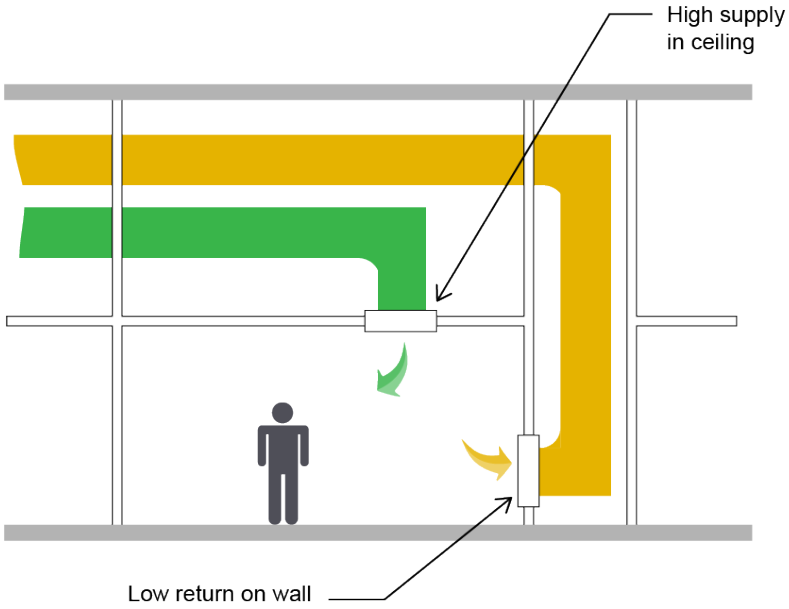

Figure 5. Low wall return diagram.

Pressurization

In a properly maintained HVAC system, pressurization moves air from clean to less clean spaces and mitigates occupants' chances of exposure to contaminated air. Typically, rooms with contaminants are set at a negative relative air pressure in order to contain contaminants in the space where they are generated. Conversely, a positive relative air pressure minimizes and pushes out contaminants in spaces that may house an immunocompromised patient (e.g., OR or protective environment [PE] room).[41]

Air will be induced to the room via small openings around the door frame when the door is closed. In signage, pressure is indicated by the following symbols inside a triangle:

- + for positive
- 0 for neutral
- — for negative

Transfer air for negative or positive pressurization purposes is indicated by a broken arrow as seen in Figure 6.[42]

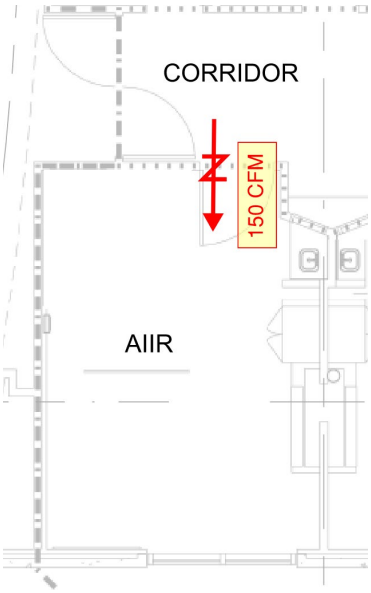

Figure 6. Transfer air symbol for negative pressurization.

Figure 7 and Figure 8 show interior perspectives of a negative room and positive room, respectively. In Figure 7, the tissue paper at the bottom of the door is being blown into the room as air comes in from the gaps around the door. In Figure 8, the tissue paper is forced tight to the door as air is sucked in around the gaps.

Figure 7. View from inside a negative pressure room.

Figure 8. View from inside a positive pressure room.

Dilution

Dilution refers to replacing the volume of air contained within a space with fresh supply air from the HVAC equipment,[43] reducing the number of hazardous particles. Increasing the airflow supply rate to the room also increases the ACH as well as the HVAC equipment's particulate removal efficiency.[44] See Table 2 for decontamination times for spaces with increasing ACH.[45] It is important to note an ACH of one does not decontaminate the room in one hour. Because of diffusion and mixing of air in the room, it takes more ACHs than simple arithmetic might imply to effectively dilute and remove contaminants to the required levels.

ACH	99% Efficiency (minutes)	99.9% Efficiency (minutes)
2	138	207
4	69	104
6	46	69
7	35	52
10	28	41
12	23	35
15	18	28
20	14	21
50	6	8

Table 2. Decontamination times for varying ACH per CDC.[46]

A room's ACH is determined by its volume (area multiplied by ceiling height) and airflow rate. Formula 1 shows the calculation, where V is volume in cubic feet (ft^3), CFM is airflow rate in cubic feet per minute (also written as ft^3/min), and 60 is a constant for minutes in an hour. Per ANSI/ASHRAE/ASHE Standard 170, the airflow rate should be measured at the return or exhaust grille for a space under negative pressurization, and at the supply grille for rooms under positive pressurization. This will ensure air transferred from one space to another for pressurization purposes is accounted for in the correct space.[47] Formula 2 rearranges Formula 1 to solve for required airflow instead of ACH.

$$ACH = \frac{(60 \times CFM)}{V}$$

Formula 1. Air changes per hour.

$$CFM = \frac{(ACH \times V)}{60}$$

Formula 2: Airflow rate.

Airborne Infection Isolation Rooms (AIIRs)

An airborne infection isolation room (AIIR) is a space designed to house patients under investigation or confirmed positive for airborne infectious diseases[48] (e.g., tuberculosis, measles and varicella-zoster virus) that can travel longer distances in air or remain suspended in air over long periods of time.[49] In order to increase the dilution of contaminants in the room, AIIRs have a higher ACH rate than comparable patient rooms housing noninfectious patients. For example, an AIIR room will have at least 12 ACH while an acute care patient room will have a minimum of 4 ACH. An intensive care unit (ICU) or critical care unit (CCU) will have at least 6 ACH.[50] ANSI/ASHRAE/ASHE Standard 170 requires that AIIR air be exhausted directly to the outdoors via a dedicated AIIR exhaust system with a fan, typically on a roof area with a discharge stack to expel the hazardous air away from the hospital.[51]

An AIIR has a negative pressure relationship to the corridor, which is accomplished by increasing supply air beyond the corridor's ventilation requirements and then exhausting the air not returned in the corridor out of the AIIR. When the room is in use, the door should be closed at all times except as necessary for designated clinical team members wearing appropriate protective equipment.[52] Any time an aerosol-generating procedure (AGP) is taking place on an individual under investigation or confirmed positive for an airborne infectious disease, the procedure should be performed in an AIIR.[53]

AIIRs are under negative pressure to protect occupants in adjacent spaces and have an increased ACH to dilute the air inside the space at a faster rate. Figure 9 demonstrates negative pressure to an AIIR and how hazardous particles are discharged after an AGP.

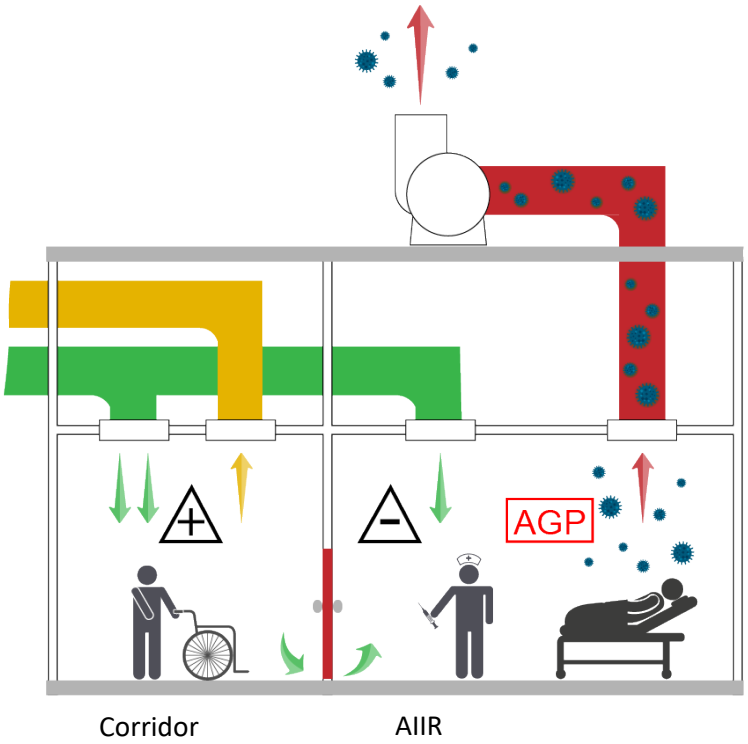

Figure 9. AGP taking place in AIIR.

Protective Environment (PE) Rooms

Conversely to AIIRs, protective environment (PE) rooms are designed to hold immunocompromised patients and protect them from any potential contaminants in the air in adjacent spaces. The PE room operates under the same principles as an AIIR: pressure relationships (aka directional airflow), a closed door and an increased ACH (12 ACH per ANSI/ASHRAE/ASHE Standard 170).[54]

However, PE rooms are not the same as AIIRs and must be used differently. A PE room will have a positive relationship to adjacent spaces to keep any airborne contaminants out for the immunocompromised individual's safety. Also, unlike an AIIR, a PE room does not need to be exhausted to the outdoors because the susceptible individual is not a hazard to other building occupants.[55]

	AIIR	PE
ACH	12	12
Pressurization	Negative	Positive
Exhausted	Yes	No
Intended for	Patients with airborne infectious diseases	Immunocompromised patients

Table 3. AIIR vs. PE rooms.

Other Factors

There are gradients of HVAC configurations at various types of health care facilities. Inpatient facilities may have administrative offices built to differing standards, and the same limitations or greater variability may be found in outpatient environments. Buildings designed to meet the less stringent requirements of ANSI/ASHRAE Standard 62.1, such as outpatient facilities, do not have the air changes, filtration levels or outdoor air quantities required by ANSI/ASHRAE/ASHE Standard 170.[56]

For example, an ambulatory surgery center (ASC) may have similar HVAC features to an inpatient facility while a medical office building (MOB) may be simplified and incapable of supporting more complex uses.[57] HVAC system modification, the use of portable HEPA filters and/or other supplemental actions are required to increase ACH, enhance filtration levels and/or establish a pressure relationship between adjacent spaces in compliance with ANSI/ASHRAE/ASHE Standard 170.[58]

Figure 10 is a schematic of a common HVAC arrangement in an outpatient facility that is permissible by ANSI/ASHRAE Standard 62.1 but not ANSI/ASHRAE/ASHE Standard 170.[59] In this example, the HVAC system utilizes a plenum return, meaning the return air travels back from individual spaces to the air handler return main via the clear area in the above-ceiling

plenum (in lieu of a return air duct system). This arrangement may result in unintended migration of potential contaminants.

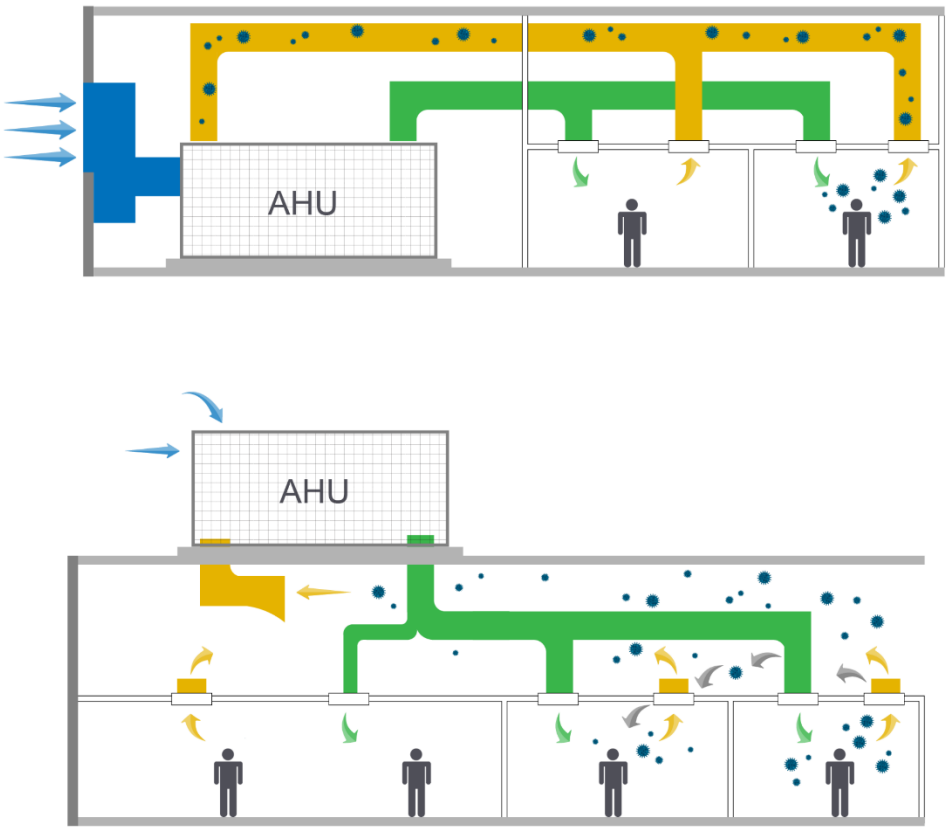

Figure 10. Ducted and plenum return.

Best Practices and Recommendations

Many times building owners desire a building designed to exceed minimum code requirements in an effort to achieve higher resiliency, better operational performance and an enhanced occupant experience. The following are recommendations to achieve these targets for infection control pertaining to heating, ventilation and air-conditioning (HVAC) systems.

Communication

Health care facilities managers play an essential role in helping clinical staff understand the function of the HVAC system. A clinical team that is aware of the functional differences

between spaces and informed of the system's capabilities and limitations can better prepare for needs that may arise and effectively respond to the requirements of individual patients.[60]

As mentioned earlier in this document, ANSI/ASHRAE/ASHE Standard 170 requires the air from certain hospital areas to be exhausted directly to the outdoors (e.g., radiology waiting rooms, emergency waiting rooms, triages, endoscopy and bronchoscopy).[61] These spaces and those with similar requirements should be considered when temporarily locating or performing procedures on patients with an airborne infectious disease. [62]

System Upgrades

Building codes for health care facilities are frequently updated to assure they include up-to-date standards and requirements for safer, more resilient buildings. It is important to note that buildings and building areas operate by the code requirements from the time the area was built or most recently renovated, not by the most recent code requirements.[63] For example a space formerly known as a Class A operating room that was renovated in 2012 might operate to the 2008 version of Standard 170 requiring 15 ACH instead of the 20 ACH required in Standard 170 versions 2013 and later.

When an HVAC system modification or upgrade is desired or required, it is critical to consider the impact to code compliance when planning the change. In addition, conduct a system test and balance (TAB) survey as applicable to assess system performance. In most jurisdictions, modifications to the HVAC system's supply, return, outside or exhaust airflow rates

are subject to the review and approval of the authority having jurisdiction (AHJ). If a system is already not performing as intended, an upgrade also may not perform as intended and could even cause additional problems to arise. It is also important to remember that certain modifications may be limited or only be feasible during certain times of the year. For example, in a cold climate during heating season, or a hot climate during cooling season, the capacity limitations of the existing HVAC equipment might make increasing outdoor air unfeasible. Whenever making alterations to the HVAC system, it is recommended to work with a reputable engineering firm with experience working in facility types similar to yours. American Society for Health Care Engineering (ASHE) members often meet such criteria, as ASHE provides certification, education and advocacy specifically for health care facilities management.

Maintenance

Routine maintenance on the HVAC system must be performed correctly to avoid compromising the HVAC system's abilities to filter, dilute, temper or pressurize. For example, if a filter has been installed incorrectly, contaminated air will bypass the filter and pass through the HVAC equipment.

An effective way to monitor air filter status is to install pressure monitors before the filter intake and after the filter discharge. As the filter absorbs contaminants, the pressure differential will increase. When the filter reaches the manufacturer's service limit for pressure differential, it is time to plan replacement filter maintenance.[64]

If a filter is not replaced, an air-handling unit (AHU) will not be capable of maintaining downstream pressure relationships and ACHs. One way to confirm a new filter has been effectively installed is to verify using a $PM_{2.5}$ particle counter, which counts fine inhalable particles. In an inpatient facility, the particle counter should read zero after a new filter has been correctly installed. Because outpatient facilities may not have the same filtration levels, the counter may read higher than zero when used in those spaces. In such cases, a lower number after filter replacement indicates correct installation.[65]

Other forms of maintenance that can impact building occupants' health include controlling the biofilm buildup (a slime containing large numbers of microorganisms) on coils inside cooling equipment and monitoring the water quality in hydronic systems. This is particularly true for open-circuit condenser water systems (i.e., cooling towers), as there is a high potential for bacterial growth in these systems.

Relative Humidity

HVAC equipment also helps control space temperature and relative humidity to a range optimized for preventing proliferation of microbes and other important parameters. Figure 11 illustrates the Sterling Risk Chart, which indicates the optimum range of relative humidity in a space is between 40% and 60%.[66]

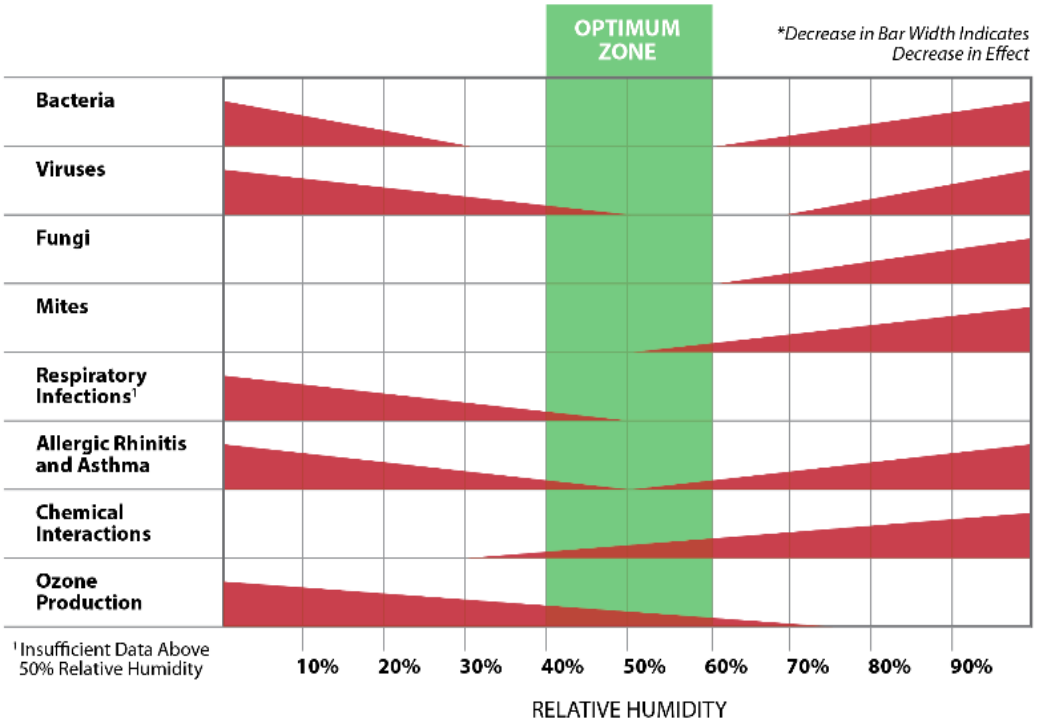

Figure 11. Sterling Risk Chart for Relative Humidity.

Pressure Monitors

As discussed previously in this document, it is critically important to ensure that an airborne infection isolation room's (AIIR's) pressure relationship and air changes per hour (ACHs) are maintained so patients with airborne infectious diseases can be housed safely when admitted to the hospital. Pressure monitors like the one shown in Figure 12 should be checked to ensure the room is kept negative. At least once per year, a balometer should be used to verify the supply air quantity and thus total ACH. If feasible, a facility team may choose to maintain one AIIR as a dedicated aerosol-generating procedure (AGP) space. An AGP is a type of procedure performed on patients that is more likely to generate high concentrations of respiratory aerosols than coughing, sneezing, talking or breathing.[67] Alternatively, a team planning a hospital may include at least one AIIR treatment room in one or more departments (e.g., the emergency or respiratory therapy departments) when designing the building.

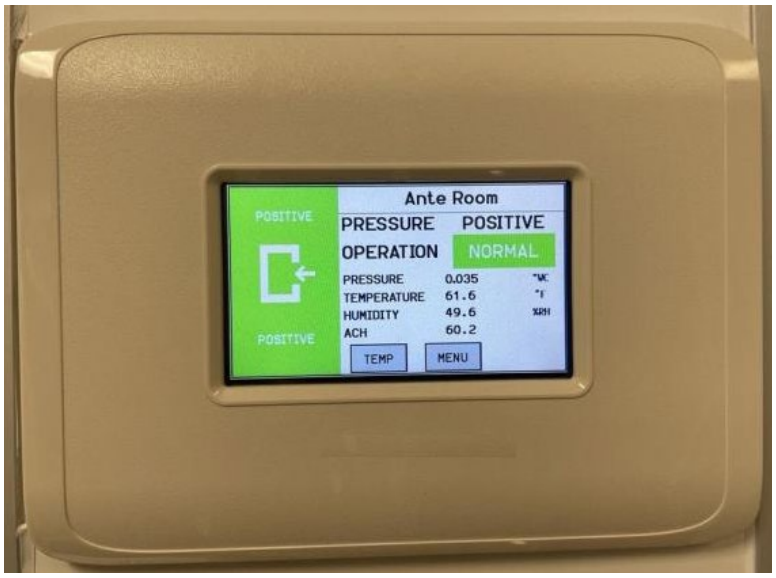

Figure 12. Room pressure monitor.

Anterooms

An anteroom, seen in Figure 13, is a small room between the AIIR and the corridor or other adjacent spaces. An anteroom creates a more resilient pressure relationship between two spaces by functioning similarly to an air lock.[68] Proper anteroom design should include a supply and exhaust grille.[69] When the isolation room is in use, the anteroom door should be closed with managed access similar to the isolation room as noted in the AIIR section. The anteroom should not be used for storage, except as dictated by the clinical team related to hand-washing and donning/doffing protective equipment. Isolation rooms not equipped with an anteroom will require adequate space in the corridor for hand-washing and donning/doffing (putting on/removing) protective equipment.[70] Figure 12 also indicates the pressurization relationship between the adjacent space, anteroom and AIIR. The anteroom is negative to the corridor, and the AIIR is negative to the anteroom. This provides a constant negative pressure relationship to the AIIR regardless if an individual is entering or leaving the room.

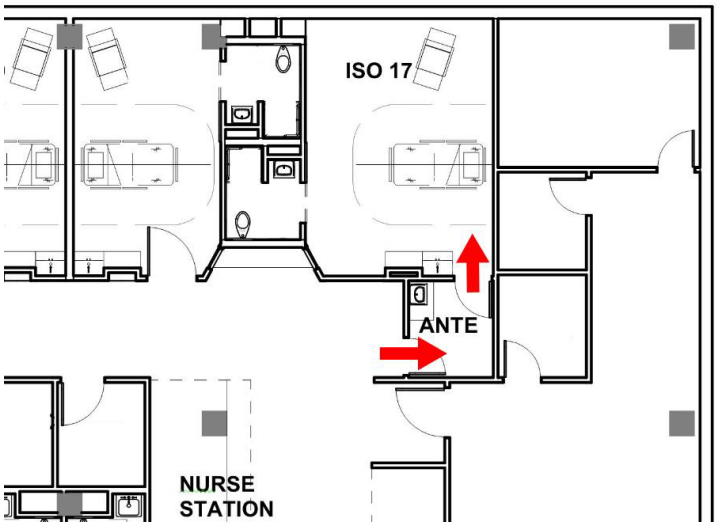

Figure 13. Pressurization relationships of an AIIR anteroom.

Personal Protective Equipment

When working in or bringing materials to an infectious disease area, personal protective equipment (PPE) must always be worn, whether or not an individual is physically entering a patient room. This requirement applies to health care facilities managers and personnel, HVAC technicians, environmental services (EVS) personnel, clinicians and administrative workers in these areas.[71] If not absolutely necessary, it is inadvisable to pass through an area housing an infected patient and building occupants should use alternate routes.

HVAC systems alone are incapable of protecting someone in the same room as an infectious patient. PPE is always required.[72]

New and Emerging Technology

Ultraviolet germicidal irradiation (UVGI) uses ultraviolet (UV) light energy to inactivate harmful microbes.[73] In facilities, UVGI is commonly applied in three ways: as indirect lights supplementing space treatment, in air-handling units, and as a supplemental air cleaner in conjunction with a high efficiency particulate air (HEPA) filter. These three methods are detailed here.

- **Upper-room UVGI** uses indirect UV lights (directed at the ceiling) to inactivate harmful microorganisms as they pass through the upper portion of a building space.[74] This method should not be relied upon as a sole means of infection prevention. Consideration must be given to the finishes in the building and if UV light could cause them to degrade.
- **UVGI in an AHU** involves placing UV lights inside the unit to reduce biofilm (a slime containing large numbers of microorganisms) on components that

experience high amounts of condensation such as cooling coils.[75] UVGI can also be a supplemental treatment to air passing through the AHU by inactivating microorganisms, but this method can be challenging to implement. [76]

- **Lighting using UVGI in HEPA filters** increases their performance. It is worth noting that a HEPA filter alone has at least a 99.97% particle efficiency rate, so any improvement to this is minor and may not have any clinical impact.[77]

Other new and emerging technology includes air-cleaning or purification devices that employ ionization, which have been marketed as a way to reduce dust, microbes and some volatile organic compounds (VOCs).

Careful consideration should be given whether new and emerging technologies are proven safe and effective. Devices must meet industry standards, and claims made by the manufacturer must be verified by reputable third-party agencies (e.g., Air-Conditioning, Heating, and Refrigeration Institute [AHRI], International Organization for Standards [ISO], Underwriters Laboratories [UL], etc. and the Food and Drug Administration [FDA] for medical devices).[78]

Conclusion

A health care facility has myriad resources for infection control, and HVAC is one of the most powerful. Together, the resources employed by a facility comprise the infection control system. Like most systems, if one component does not function correctly, the system will fail to perform its purpose, which in this case is to prevent infections from spreading. HVAC's role in the infection control system is primarily to provide pressurization between spaces and remove airborne contaminants, two effects practically invisible to the naked eye. It is paramount for any facility team to keep a watchful eye on the HVAC system's gauges, monitors and TAB reports to verify the HVAC system's ability to operate as desired, allowing the health care facility's infection control system to perform for the safety of all the occupants.

Case Studies

Case Study A: FGI 2021

https://fgiguidelines.org/wp-content/uploads/2021/04/FGI_Guidance_for_Facilities_that_Respond_and_Adapt_to_Emergency_Conditions.pdf

The Facility Guidelines Institute (FGI) released a document in March 2021 titled “Guidance for Designing Health and Residential Care Facilities that Respond and Adapt to Emergency Conditions,” within which is a case study highlighting an academic medical center in the mid-Atlantic region of the United States and its facilities’ response to the COVID-19 pandemic.[79]

One of the most noteworthy points raised in the case study is that in a health care institution with over 14 hospitals, serving over 13,000 COVID-19 patients (nearly 4,000 inpatient) and simultaneously caring for 17,000 patients not positive for COVID-19, there was no evidence of COVID-19 transmission. This indicates that a hospital can be a safe place for all occupants even during a pandemic, with the proper measures in place.[80]

The document adopted a version of Taylor’s 2014 “The Environment of Safe Care: Considering Building Design as One Facet of Safety,” shown in Figure 14. The figure indicates how as the building’s design progresses through design and into construction, the cost of implementing safety features increases greatly, as the ease of implementation into the facility drastically decreases. This figure should be remembered when debating the feasibility, effectiveness and cost of implementing design changes at various stages of design, construction or occupancy.[81]

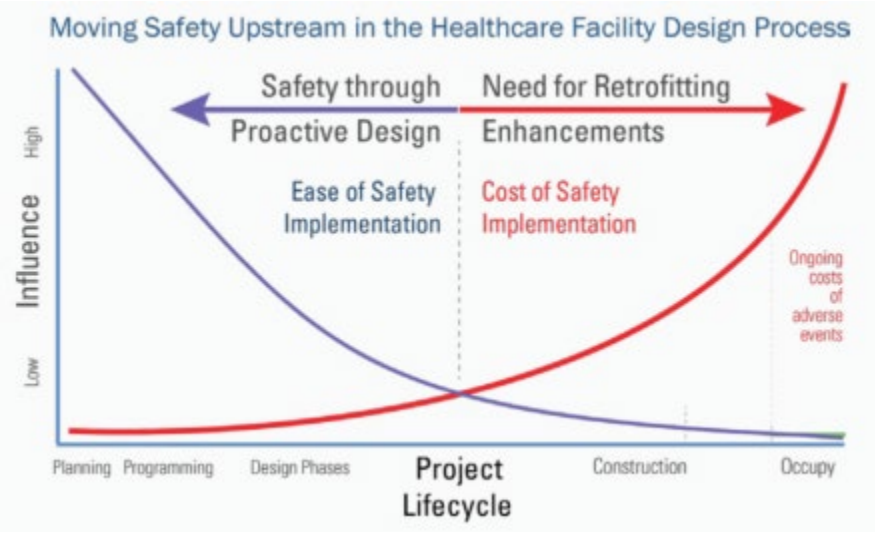

Figure 14. Moving safety upstream in the healthcare facility design process. Courtesy of FGI.

Case Study B: Shobha Subhash 2013

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7135637/

An article titled “Isolation anterooms: Important components of airborne infection control” emphasizes the value of isolation anterooms and provides examples, including an instance where infection control measures were compromised and its ramifications.[82]

The case study goes into detail about the efficacy of anterooms and the enhanced safety they provide to building occupants from infectious diseases. The document notes that in airborne infection isolation rooms (AIIRs) without anterooms, the differential pressure relationship is lost once the door opens, and the resulting air movement dynamics and piston effect create an opportunity for hazardous particles to migrate out of the room and into adjacent spaces.[83]

The document further proves this point by discussing the case of a nurse who contracted chickenpox from a patient housed in an AIIR, despite never entering the AIIR. The nurse believed that due to the room’s negative pressure, it was safe to walk past the room or hand medical instruments to clinical colleagues standing in the doorway without entering the room. Hazardous particles spread outside of the AIIR and infected the nurse. Had the AIIR been designed to include an anteroom, the particles would not have migrated into the corridor and the nurse likely would not have contracted chicken pox. With or without an anteroom, proper protocols related to door closure should be emphasized while the AIIR is in use and access limited to necessary staff only.[84]

Case Study C: Health Care Facility in Southeastern US 2020

A strategy used by a hospital in the Southeastern United States during the COVID-19 pandemic is highlighted in Figure 14. Here, the facility opted to make regular patient rooms slightly negative and HEPA filter the air from the patient rooms.

This strategy was accomplished by increasing supply airflow in the corridors, blocking off the return diffusers in the corridors, and connecting the HEPA machine discharge to the return air grille via flexible ductwork. This creates a negative relationship between the patient rooms and the corridor, though not as resilient as the negative pressure relationship an AIIR has to its adjacent spaces, which is required to be indicated with a room pressure monitor. However, the hospital’s configuration returned the HEPA-filtered air to the AHU instead of exhausting it to the outdoors as an AIIR does, which uses less energy and does not require upgrades to the AHU’s heating or cooling capacity.

Please note that Figure 15 is an image taken from an overall air balance drawing. Values do not reflect all of the changes made, and a complete AHU test and air balance (TAB) should be done when making modifications.

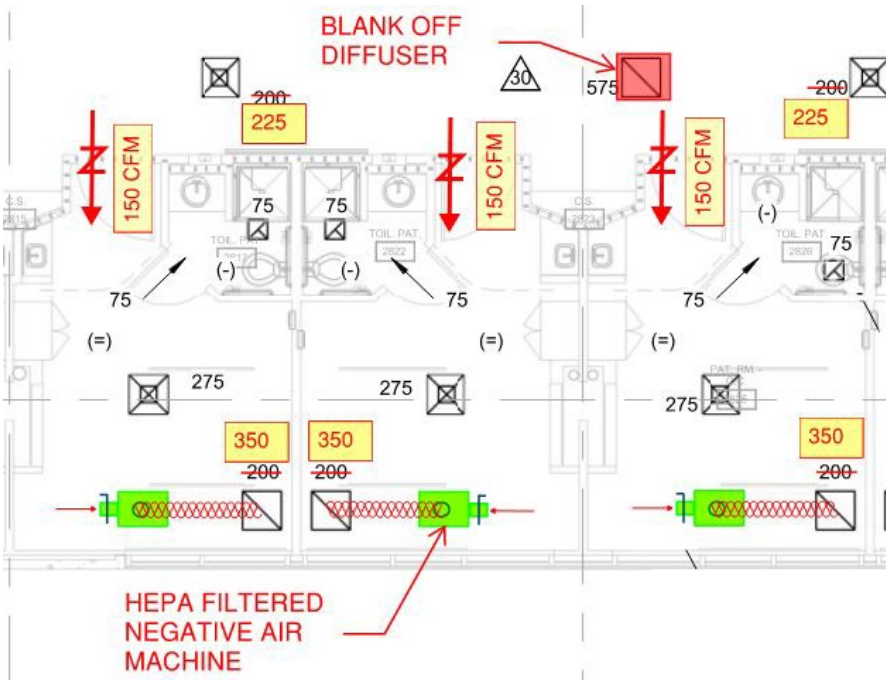

Figure 15. Slightly negative HEPA-filtered patient room.

Tools

- Project Firstline Quick Guide on HVAC's Role in Infection Control for Health Care Facilities Managers (2022)
- Project Firstline Professional Development on HVAC's Role in Infection Control for Health Care Facilities Managers (2022)
- Infection Control Guide on Heating, Ventilation and Air Conditioning (HVAC) for Nurse Managers and Clinicians (2022)
- Infection Control Guide on Heating, Ventilation and Air Conditioning (HVAC) for HVAC Technicians (2022)
- CDC "Guidelines for Environmental Infection Control in Health-Care Facilities" (July 2019)
- CDC Project Firstline
- Minnesota Department of Health Office of Emergency Preparedness Program. "Airborne Infectious Disease Management, Methods for Temporary Negative Pressure Isolation" (February 2020)
- ANSI/ASHRAE/ASHE Standard 170, *Ventilation of Health Care Facilities* (2021)
- ANSI/ASHRAE Standard 52.2, *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size* (2017)
- ANSI/ASHRAE Standard 62.1, *Ventilation for Acceptable Indoor Air Quality* (2019)
- *American Journal of Infection Control*, "Isolation anterooms: important components of airborne infection control" (2013)
- FGI *Guidelines for Design and Construction of Healthcare Facilities* (2008)
- EPA Particulate Matter (PM) Basics

Glossary

Accrediting organization – A group endowed with the ability to grant accreditation.

ACH – Air changes per hour – The number of times the air is replaced per hour in the room. Replacing the air volume in the room once DOES NOT mean the room is decontaminated. See Table 2 on ACH decontamination times for recommended timeline to entering a hazardous room.

Addenda – Changes to an official document published between, and then typically incorporated into, the document republication.

AGP – Aerosol-generating procedure – A medical procedure that produces large amounts of aerosol particles, particularly those derived from respiratory fluids.

AHJ – Authority having jurisdiction – The agent or agency responsible for enforcing a standard.

AHRI – Air-Conditioning, Heating, and Refrigeration Institute

AHU – Air-handling unit – HVAC component responsible for filtering, conditioning and moving the air around a building. See also **central station AHU**.

AIIR – Airborne infection isolation room – A room designed to the requirements of ANSI/ASHRAE/ASHE Standard 170 that is intended to provide airborne infection isolation.

ANSI – American National Standards Institute – U.S. governmental organization responsible for overseeing development of voluntary consensus standards for products, services, processes, systems, and personnel. Involved in the publication of ANSI/ASHRAE Standard 62.1*, Ventilation for Acceptable Indoor Air* Quality and ANSI/ASHRAE/ASHE Standard 170*, Ventilation of Health Care Facilities*.

ASC – Ambulatory surgery center – A distinct surgical entity that operates exclusively to provide surgical care to patients not requiring hospitalization or an expected service duration of over 24 hours following admission. An ASC may have similar infection control provisions as a hospital.

ASHE – American Society for Health Care Engineering – An association of professionals who design, build, maintain and operate hospitals and other health care facilities, a trusted resource that provides education, regulatory guidance, advocacy representation and professional development. Involved in the publication of ANSI/ASHRAE/ASHE Standard 170*, Ventilation of Health Care Facilities*.

ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers – An international society of engineers responsible for producing standards for and performing research of HVAC systems. Involved in the publication of:

- ASHRAE Standard 52.2, *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*
- ANSI/ASHRAE Standard 62.1, *Ventilation for Acceptable Indoor Air Quality*
- ANSI/ASHRAE/ASHE Standard 170, *Ventilation of Health Care Facilities*

Balometer – An air measuring device placed at the air inlet or outlet to a room to determine airflow in a space,

Central station air-handling unit – A large piece of HVAC equipment typically in its own room or on the roof, responsible for heating, cooling, filtering, mixing and blowing the air around the facility.

Challenge testing – A process to test the competency of a product or method to verify claims made about the product or method.

CMS – Centers for Medicare & Medicaid Services – Part of the U.S. Department of Health and Human Services, plays a critical role in health care regulatory compliance.

Contaminant – A polluting substance that causes an impurity considered to be undesirable.

Diffusion – Movement or dispersion of an element from one concentration to another.

FDA – Federal Agency of the Department of Health and Human Services in the United States responsible for protecting the public health by ensuring the safety, efficacy, and security of human and veterinary drugs, biological products, and medical devices; and by ensuring the safety of the United States' food supply, cosmetics, and products that emit radiation.

FCU – Fan coil unit – A piece of HVAC equipment responsible for cooling or heating air only. Similar to an AHU but typically only serves one space and does not have infection control capabilities.

FGI – The Facility Guidelines Institute – Organization working to develop guidelines dedicated to designing and building hospitals and other health care facilities. Relevant publications include:

- *FGI Guidelines for Design and Construction of Hospitals*
- *FGI Guidelines for Design and Construction of Outpatient Facilities*
- *FGI Guidelines for Design and Construction of Residential Health, Care, and Support Facilities*

Final filter – An air filter designed to be the final level of filtration before air leaves a piece of equipment. Intended to remove very fine particles from the air.

HEPA – High efficiency particulate air (filter) – A mechanical air filter capable of filtering at least 99.97% of airborne particles.

HVAC – Heating, ventilation and air-conditioning (system) – Building system responsible for tempering, pressurizing, and ventilating the building.

ICU – Intensive care unit – A patient room dedicated to housing patients in a more severe condition, or released from a demanding medical procedure. Can also be referred to as a critical care unit (CCU).

ISO – International Organization for Standardization – An international organization dedicated to producing standards across many products and companies.

MERV – Minimum efficiency reporting value – Rating value developed by ASHRAE to report a filter's ability to capture particles at varying size. A higher MERV rating indicates a higher performing filter.

MOB – Medical office building – An office building designed specifically for health care. An MOB likely does not have the same infection control capabilities as a hospital.

Negative air pressure – Pressurization in which air is sucked into a space in order to contain contaminants at their point of origin.

OR – Operating room – A surgical room where medical operations and surgeries occur.

OSA – Outside air – Air from the outside that is brought in to establish pressure relationships and dilute recirculated return air from the building.

PE – Protective environment – A room designed to hold immunocompromised patients and protect them from any potential contaminants in the air in adjacent spaces

Piston effect – When a room and door act to force airflow in or out of a room as the door is opened.

Plume – Airflow pattern once air has been dispersed from something (e.g., air leaving a person's mouth as they sneeze or air being expelled from an exhaust fan).

PM – Particulate matter – Term for solid and liquid particulate suspended in the air.

Pre-filter – An air filter placed at the inlet of HVAC equipment designed to capture dust and large particles that could damage components inside the equipment.

Positive air pressure – Pressurization in which air is pushed out of a space in order to prevent airborne contaminants from adjacent spaces entering a room.

TAB – Testing and balancing – Measuring, adjusting and calibrating pieces of an HVAC system to ensure its performance is as designed.

TJC – The Joint Commission – An accrediting organization responsible for accrediting hospitals and improving health care safety.

UL – Underwriters Laboratories – An organization dedicated to advancing public safety. Provides a certification of marketed products.

UV – Ultraviolet – A form of electromagnetic radiation with shorter wavelengths than visible light, so it is not seen by the human eye. At the right intensity UV lights have shown to inactivate pathogens.

UVGI – Ultraviolet germicidal irradiation – The use of ultraviolet energy to kill or inactivate viral, bacterial and fungal species.

VOC – Volatile organic compound – A compound emitted as a gas that can have short and long-term health effects.

Endnotes

[1] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*, Standard 52.2. Atlanta: ASHRAE, 2017.
[2] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021; American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Ventilation for Acceptable Indoor Air Quality*, Standard 62.1. Atlanta: ASHRAE, 2019.
[3] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[4] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021; American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Ventilation for Acceptable Indoor Air Quality*, Standard 62.1. Atlanta: ASHRAE, 2019.
[5] American Society of Heating, Refrigerating and Air-Conditioning Engineers. *HVAC Design Manual for Hospitals and Clinics*. 2nd edition. Atlanta: ASHRAE, 2013.
[6] Memarzadeh, Farad. "The Environment of Care and Health Care-Associated Infections: An Engineering Perspective." Chicago: American Society for Health Care Engineering, 2011.
[7] Centers for Disease Control and Prevention. "Guidelines for Environmental Infection Control in Health-Care Facilities." 2019 edition. Atlanta: CDC, 2003.
[8] The Facility Guidelines Institute. *Guidelines for Design and Construction of Hospitals*. Dallas: FGI, 2018; FGI. *Guidelines for Design and Construction of Outpatient Facilities*. Dallas: FGI, 2018; FGI. *Guidelines for Design and Construction of Residential Health, Care, and Support Facilities.* Dallas: FGI, 2018.
[9] See note 8.
[10] See note 8.
[11] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[12] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*, Standard 52.2. Atlanta: ASHRAE, 2017.
[13] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Ventilation for Acceptable Indoor Air Quality*, Standard 62.1. Atlanta: ASHRAE, 2019.
[14] See note 13.
[15] See note 13.
[16] See note 13.
[17] Centers for Medicare & Medicaid Services. “About CMS.” Accessed in 2021. https://www.cms.gov/About-CMS/About-CMS
[18] See note 17.
[19] The Joint Commission. “About Us.” Accessed in 2021. https://www.jointcommission.org/about-us/
[20] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[21] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Ventilation for Acceptable Indoor Air Quality*, Standard 62.1. Atlanta: ASHRAE, 2019.
[22] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[23]American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Ventilation for Acceptable Indoor Air Quality*, Standard 62.1. Atlanta: ASHRAE, 2019.
[24] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[25] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Ventilation for Acceptable Indoor Air Quality*, Standard 62.1. Atlanta: ASHRAE, 2019.
[26] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*, Standard 52.2. Atlanta: ASHRAE, 2017.
[27] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Ventilation for Acceptable Indoor Air Quality*, Standard 62.1. Atlanta: ASHRAE, 2019.
[28] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[29] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*, Standard 52.2. Atlanta: ASHRAE, 2017.
[30] United States Environmental Protection Agency. “Particulate Matter (PM) Basics.” Accessed in 2021. District of Columbia: EPA. https://www.epa.gov/pm-pollution/particulate-matter7
-pm-basics
[31] United States Department of Energy. *DOE Handbook: Nuclear Air Cleaning Handbook*. District of Columbia: DOE, 2003.

[32] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[33] See note 32.
[34] American Society of Heating, Refrigerating and Air-Conditioning Engineers. *ASHRAE Handbook–HVAC Systems and Equipment*. Atlanta: ASHRAE, 2020.
[35] See note 34.
[36] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[37] Hermans, R.D. "The Search for Minimum Protection: How Safe Do Healthcare Facilities Need to Be?" Research conducted for the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, June 2019.
[38] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[39] See note 38.
[40] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*, Standard 52.2. Atlanta: ASHRAE, 2017.
[41] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[42] American Society of Heating, Refrigerating and Air-Conditioning Engineers. *ASHRAE Handbook–HVAC Fundamentals*. Atlanta: ASHRAE, 2021.
[43] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[44] Centers for Disease Control and Prevention. "Guidelines for Environmental Infection Control in Health-Care Facilities." 2019 edition. Atlanta: CDC, 2003.
[45] See note 44.
[46] See note 44.
[47] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[48] See note 47.
[49] Centers for Disease Control and Prevention. "Guidelines for Environmental Infection Control in Health-Care Facilities." 2019 edition. Atlanta: CDC, 2003.
[50] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[51] See note 50.
[52] See note 50.
[53] Centers for Disease Control and Prevention. "Interim Infection Prevention and Control Recommendations for Healthcare Personnel During the Coronavirus Disease 2019 (COVID-19) Pandemic" CDC, 2022. https://www.cdc.gov/coronavirus/2019-ncov/hcp/infection-control-recommendations.html
[54] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[55] See note 54.
[56] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Ventilation for Acceptable Indoor Air Quality*, Standard 62.1. Atlanta: ASHRAE, 2019.
[57] The Facility Guidelines Institute. *Guidelines for Design and Construction of Hospitals*. Dallas: FGI, 2018; FGI. *Guidelines for Design and Construction of Outpatient Facilities*. Dallas: FGI, 2018; FGI. *Guidelines for Design and Construction of Residential Health, Care, and Support Facilities.* Dallas: FGI, 2018.
[58] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[59] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021; American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Ventilation for Acceptable Indoor Air Quality*, Standard 62.1. Atlanta: ASHRAE, 2019.
[60] American Society for Health Care Engineering, et al., *Using the Health Care Physical Environment to Prevent and Control Infection.* Chicago: AHA, 2018. https://www.ashe.org/infectionprevention
[61] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. *Ventilation of Health Care Facilities,* Standard 170. Atlanta: ASHRAE, 2021.
[62] See note 61.
[63] See note 61.
[64] American Society of Heating, Refrigerating and Air-Conditioning Engineers. *ASHRAE Handbook–HVAC Applications.* Atlanta: ASHRAE, 2019.
[65] See note 64.
[66] Arundel, Anthony V., Elia M. Sterling, Judith H. Biggin, and Theodor D. Sterling. "Indirect Health Effects of Relative Humidity in Indoor Environments." *Environmental Health Perspectives* 65 (1986): 351-361.
67 Tran, Khai, Karen Cimon, Melissa Severn, Carmem L. Pessoa-Silva, and John Conly. "Aerosol Generating Procedures and Risk of Transmission of Acute Respiratory Infections to Healthcare Workers: A Systematic Review." *PLOS ONE* 7, no. 4 (2012): e35797.
[68] Centers for Disease Control and Prevention. "Guidelines for Environmental Infection Control in Health-Care Facilities." 2019 edition. Atlanta: CDC, 2003.
[69] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers/American Society for Health Care Engineering. Ventilation of Health Care Facilities, Standard 170. Atlanta: ASHRAE, 2021.

[70] Centers for Disease Control and Prevention. "Guidelines for Environmental Infection Control in Health-Care Facilities." 2019 edition. Atlanta: CDC, 2003.
[71] American Society for Health Care Engineering, et al., *Using the Health Care Physical Environment to Prevent and Control Infection.* Chicago: AHA, 2018. https://www.ashe.org/infectionprevention
[72] Menzies, Dick, Anne Fanning, Lilian Yuan, J. Mark FitzGerald, and Canadian Collaborative Group in Nosocomial Transmission of TB. "Hospital Ventilation and Risk for Tuberculous Infection in Canadian Health Care Workers." *Annals of Internal Medicine* 133, no. 10 (2000): 779-789.
[73] Centers for Disease Control and Prevention. "Ventilation in Buildings." Accessed February 9, 2021. https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html
[74] See note 73.
[75] See note 73.
[76] See note 73.
[77] American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*, Standard 52.2. Atlanta: ASHRAE, 2017.
[78] Centers for Disease Control and Prevention. "Ventilation in Buildings." Accessed February 9, 2021. https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html
[79] Facility Guidelines Institute. "Guidance for Designing Health and Residential Care Facilities that Respond and Adapt to Emergency Conditions." FGI, March 2021.
[80] See note 79.
[81] See note 79.
[82] Subhash, Shobha S., Gio Baracco, Kevin P. Fennelly, Michael Hodgson, and Lewis J. Radonovich. "Isolation Anterooms: Important Components of Airborne Infection Control." *American Journal of Infection Control* 41, no. 5 (2013): 452-455.
[83] See note 82.
[84] See note 82.