

Engineering Solutions for Preventing Airborne Transmission in Hospitals with Resource Limitation and Demand Surge

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ABSTRACT

Among the various strategies for the prevention of airborne transmission, engineering measures are placed high in the hierarchy of control. Modern hospitals in high-income countries have mechanical systems of building ventilation also called HVAC (heating, ventilation, and air-conditioning) but installation and maintenance of such systems is a challenging and resource-intensive task. Even when the state-of-the-art technology was used to build airborne infection isolation rooms (AIIRs), recommended standards were often not met in field studies. The current coronavirus disease-2019 pandemic has highlighted the need to find cost-effective and less resource-intensive engineering solutions. Moreover, there is a need for the involvement of interdisciplinary teams to find innovative infection control solutions and doctors are frequently lacking in their understanding of building ventilation-related problems as well as their possible solutions. The current article describes building ventilation strategies (natural ventilation and hybrid ventilation) for hospitals where HVAC systems are either lacking or do not meet the recommended standards. Other measures like the use of portable air cleaning technologies and temporary negative-pressure rooms can be used as supplementary strategies in situations of demand surge. It can be easily understood that thermal comfort is compromised in buildings that are not mechanically fitted with HVAC systems, therefore the given building ventilation strategies are more helpful when climatic conditions are moderate or other measures are combined to maintain thermal comfort.

Keywords: Airborne transmission, Air cleaning technologies, Hybrid ventilation, Natural ventilation, Temporary negative-pressure rooms, Ventilation systems.

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INTRODUCTION

The tremendous potential of respiratory viruses to create havoc in our lives was never so well recognized as of today. The need for better hospital designs in terms of ventilation and prevention of infection transmission is one of the most important lessons being learned during the coronavirus disease-2019 (COVID-19) pandemic. The pandemic has also highlighted the knowledge gap among medical professionals regarding engineering issues of infection control and stresses the need for multidisciplinary team involvement for its management. Respiratory viruses show multimodal transmission of infection, i.e., via large respiratory droplets which settle in the nearby area due to gravitation after being expelled by infected individuals (droplet transmission), fine respiratory droplets that remain suspended in the air for hours and travel long distances (airborne transmission), and direct/ indirect contact with infected secretions (contact transmission).¹ Though there is controversy regarding the size of respiratory droplets in defining droplets and airborne transmission (<5 micron vs >5 microns), the difference is more or less arbitrary as the trajectory of respiratory droplets is a complex phenomenon and difficult to predict in different microclimates.² According to Roy et al., diseases which primarily spread via droplet transmission can also show facultative airborne transmission under favorable environmental conditions.³

Broadly, infection prevention measures for airborne transmission of respiratory pathogens in a hospital can be classified into administrative, engineering, and individual control (personal and respiratory protective equipment).⁴ Of the above three strategies, administrative and engineering control form the two basic pillars because individual control is subject to attitude failure and dependent on the availability of protective equipment. Engineering control measures are mainly determined by the ventilation system of the hospital building. After

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severe acute respiratory syndrome (SARS) 2003 epidemic, a team of multidisciplinary experts conducted a systematic review of 40 original articles and concluded that the association between airborne infection and ventilation is strongly supported by evidence but minimum ventilation requirements to prevent airborne infection transmission still remains elusive in different settings.⁵

Methods to ventilate a building include natural, mechanical (heating, ventilation and air-conditioning [HVAC] systems), and

hybrid (mixed mode). Conventional mechanical ventilation systems were found to have lower bioaerosols (20 cfu/m³, 95% confidence interval [CI]: 16–24) as compared to the naturally ventilated areas (201 cfu/m³, 95% CI: 135–300) in a systematic review of 36 studies.⁶ Authors also found that sophisticated mechanical ventilation systems with higher air changes per hour, high-efficiency particulate air (HEPA) filtration, and directional airflow were superior to conventional mechanical ventilation in terms of bioaerosol concentrations (9 cfu/m³, 95% CI: 7–13).⁶ Different societies and government bodies have given recommendations to guide the standards of HVAC systems in the hospitals.^{7–9} However, installation and maintenance of advanced mechanical systems are difficult and resource-intensive. If not maintained properly, mechanical ventilation systems can themselves become a source of infection for the hospitals.¹⁰ Wong et al. reported a SARS-CoV-1 cluster among medical students who visited a single case in a ward with imbalanced airflow rates through diffusers and exhaust grilles.¹¹ More evidence comes from the landmark paper by Li et al., which showed that despite using the state-of-art technologies for the construction of SARS isolation rooms in nine hospitals of Hong Kong, standard ventilation requirements were not met in field studies. Air change rates were <12 air change per hour (ACH) in 26% of rooms while 60% of the toilets had wrong airflow direction.¹²

These issues become even more important in resource-limited settings because advanced systems have recurring running cost along with breakdown maintenance investment after initial fixed and installation cost (e.g., cleaning of condenser and evaporator coils, regular check of HEPA filter efficiency and indoor air quality, lubrication of fans, motor, and moving parts, etc.).⁹

The current study was undertaken to provide information to medical professionals regarding viable engineering solutions for preventing airborne transmission in hospitals where mechanical ventilation (HVAC) systems are either absent or unable to meet the standard requirements.

MATERIALS AND METHODS

A literature search was done to find answers to our study question, “What are the different engineering solutions and building ventilation strategies for preventing airborne transmission in a hospital setting where conventional HVAC is lacking or does not meet the recommended standards due to resource limitation or demand surge?”

We did a literature search for studies published from 2000 to 2020 in “PubMed,” “ScienceDirect,” “Embase,” “Google Scholar,” and “Scopus,” using the following terms: “engineering solution for airborne transmission,” “ventilation and airborne transmission,” “natural ventilation and airborne transmission,” “hybrid ventilation and airborne transmission,” “temporary negative-pressure room,” and “air purification technologies” (Fig. 1). Three authors independently searched the literature on ventilation and airborne transmission, natural ventilation, and hybrid technologies while two authors did literature research on temporary negative-pressure ventilation. The literature search on air purification technologies was done by two authors. Studies which matched with the keywords were retrieved and assessed for eligibility. The difference of opinion among authors was resolved after discussion and consultation with the third author who also supervised the work of other authors.

DISCUSSION

Before going into the details of various strategies, it is important to discuss the performance indices of the ventilation system.

Building Ventilation

Ventilation is the process of changing or replacing air from any space by mechanical or natural means. The key elements defining ventilation of any building include the rate of ventilation, the direction of airflow, and the pattern of airflow.

Higher ventilation rates are considered protective as they lead to dilution of airborne pathogens.¹³ Relationship between

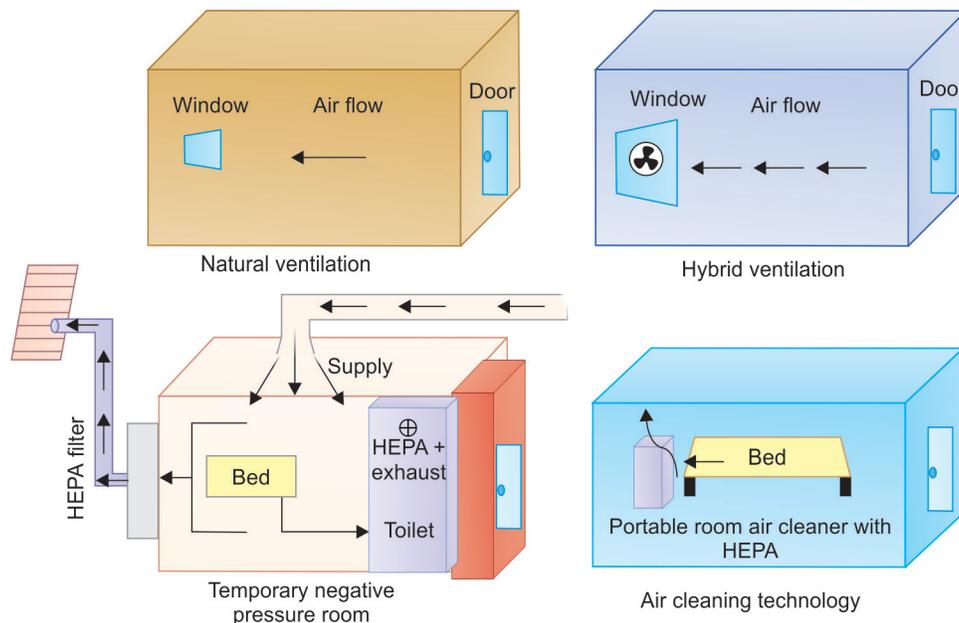


Fig. 1: Graphical abstract

ventilation rates and airborne transmission of infection was derived by Riley and is called as Wells–Riley equation given below.¹⁴

$$\text{Probability of infection} = \text{No of cases/No of susceptibles} \\ = 1 - \exp[-Iqpt/Q]$$

I is the number of infecting individuals (infectors), p is the pulmonary ventilation rate of a susceptible person (m^3/h), q is the quanta produced by one infected individual, t is the duration of exposure, and Q is the room ventilation rate with clean air (m^3/h). Most guidelines recommend a minimum ventilation rate of 12 ACH for the prevention of airborne infections.¹⁵

Besides this, the **direction of airflow** from clean to dirty area and proper distribution of fresh air are also required to prevent the transmission of airborne pathogens. Note that uninterrupted pressure difference is required to maintain the direction of airflow from clean to dirty area and has been found to be difficult to achieve in field studies.^{12,13}

The **airflow pattern** has been classically described as mixing ventilation, downward ventilation, and displacement ventilation. Among these three types, mixing ventilation uses high-momentum air supplies for even distribution of temperature and particulate matter while downward ventilation uses low-velocity clean and cooler air from the ceiling in the form of “laminar streams.” Displacement ventilation is not used in hospitals for the prevention of airborne infections.¹⁶

Assessment of Ventilation System

Any ventilation system is assessed on the basis of four factors, namely quality of indoor air, thermal comfort, removal of pollutants as well as pathogens, and energy consumption.¹⁷ Indoor air quality is mainly a function of air exchanges with the outdoor environment or filtered air if being recirculated. In order to measure the efficiency of a ventilation system, two performance indices are commonly used, namely air exchange efficiency (a measure of fresh air distribution) and ventilation effectiveness (a measure of airborne pollutant removal).¹⁸

- **Air exchange efficiency** is a measure of the effectiveness of fresh air distribution in a building. It is calculated from ACH and room mean age of air.
- **Ventilation effectiveness** is estimated by measurement or simulation and indicates how effectively the airborne pollutant is being removed from the room. The local mean age of air and room mean age of air are used to study ventilation effectiveness and tracer gas technique is used to determine the age of air. The slope of tracer gas curve, area under curve, and ratio of concentrations are different methods to determine the ventilation efficiency of a system.
- **Computational fluid dynamics (CFD)** is used for modeling air distribution performance in buildings.¹⁹ CFD involves a set of algebraic equations which are calculated for a system using digital computers.

Natural Ventilation

Natural ventilation is the process of supplying air to and removing air from an indoor space without using mechanical systems. Natural ventilation and sunlight were considered key strategies against numerous infectious diseases before the advent of mechanical ventilation. High ventilation rates in naturally ventilated hospitals with high ceilings and large windows provided protection via dilution of pathogens in olden times.²⁰

Two types of natural ventilation systems have been described in the literature.

- **Wind-driven ventilation**—arises from the difference of pressure created by the wind around a building or a structure, and opening formed on the perimeter, which then permits flow through the building.
- **Bouncy-driven ventilation**—occurs as a result of the directional bouncy force that results from the temperature difference between the interior and exterior.

According to World Health Organization 2009 guidelines on natural ventilation, the recommended average ventilation rates for the prevention of airborne infections are 80–160 liters/sec/patient for airborne isolation rooms, 60 liters/sec/patient for general wards and outpatients, and 2.5/sec/ m^3 for corridors and transient areas.²¹

Natural ventilation is economical and provides a high ventilation rate due to the use of natural forces and large openings, such as windows and doors.^{22,23} Effective utilization of sunlight can be done in naturally ventilated areas. However, such type of ventilation lacks objective parameters as they are difficult to plan, design, and predict performance, and has reduced the comfort level of occupants in extremes of weather. Most studies show that of the three determinants of a ventilation system, i.e., rate, direction, and pattern, natural ventilation is able to generate high ventilation rates which are frequently much higher than those achieved with mechanical ventilation but direction and pattern of airflow are unpredictable due to the lack of sustained negative pressure.^{24–26} This leads to a risk of contamination to corridors and adjacent rooms. The use of technology in improvising the natural ventilation system has helped overcome a few of its shortcomings.^{25,27}

Hybrid Ventilation

When natural ventilation is used along with the assisted technology to meet the ventilation requirement, it is termed as hybrid or mixed-mode ventilation. Most frequently, it is done by the installation of exhaust fans, the size and location of which are determined by the targeted ventilation rates.²⁵ Hybrid ventilation has the advantage of being suitable for most climates and weather but there can be problems due to an increase in noise level, the need for continuous supply of electricity, and difficulty in maintaining thermal comfort. **Figure 2** shows an example of converting a typical ward into an airborne transmission precaution unit by placing industrial exhausts in each cubicle such that the desired airflow pattern from the inlet openings (above the entry door) to the outlet openings on the opposite walls is achieved and exhausted air exceeds the supplied air. Note that placement of exhausts is such that the clean air is distributed evenly and pockets of stale air are avoided. Air conditioner (placed on the opposite walls) is used to maintain temperature and humidity (thermal comfort). Exhaust fans have also been provided in the central corridor to induce a larger intake of fresh air from outside.

According to various guidelines for air-conditioned healthcare facilities, in order to convert general patient rooms or intensive care units (ICUs) to one with airborne infection prevention, the first engineering step is to convert the designated space into a nonrecirculatory system (unless there is a provision for recirculation of adequately cleaned air).²⁸ Air-conditioned healthcare facilities usually have a recirculatory system. Among various measures suggested to convert such facilities to a nonrecirculatory system include completely blocking the return air vents, provision of

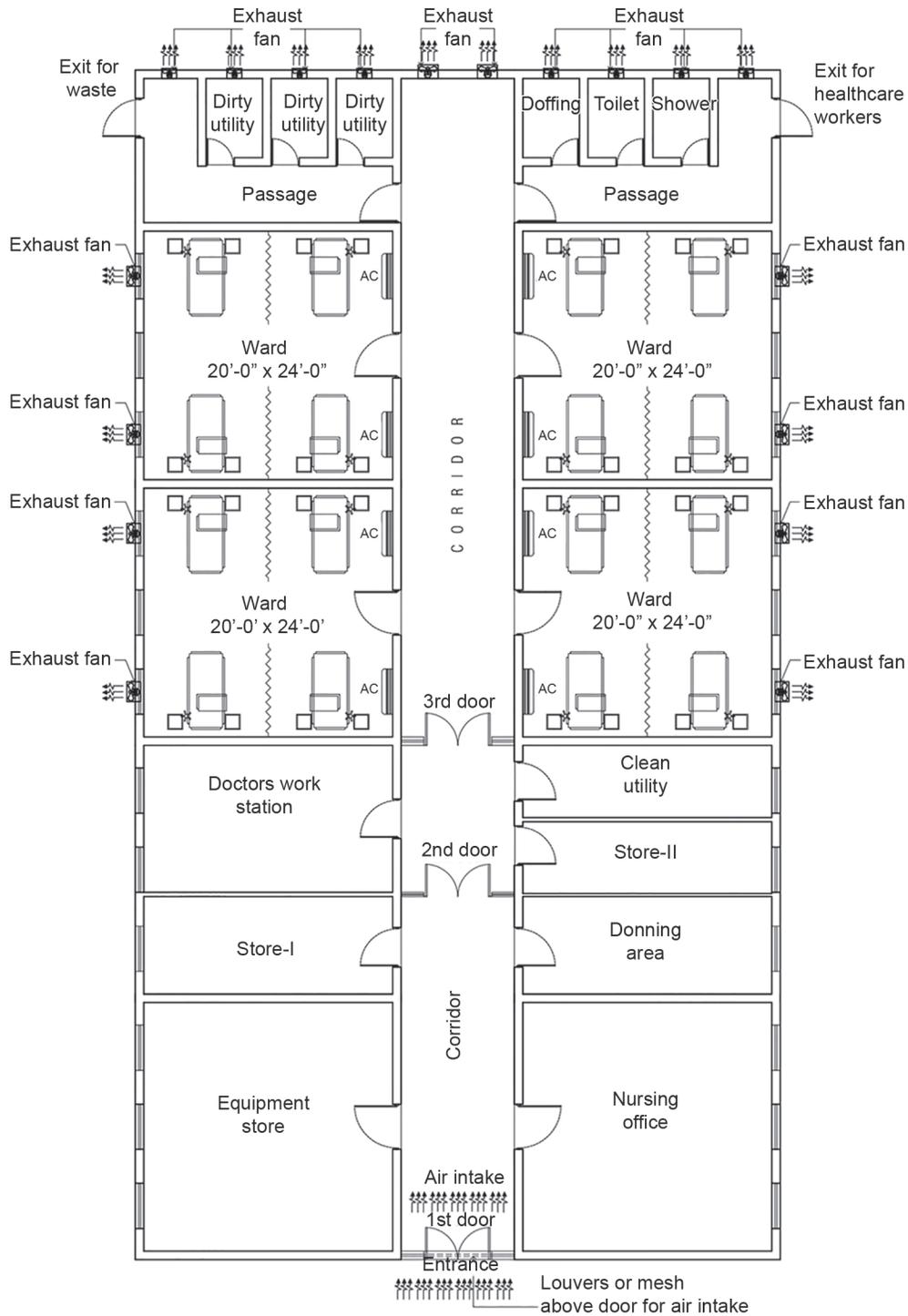


Fig. 2: Hybrid design

adequate air supply (minimum recommended 12 ACH), and provision of an independent exhaust blower to extract the room air into the outside atmosphere after “suitable cleaning/ treatment.”^{15,28–30}

If the mechanical ventilation system is inadequately designed/ unavailable, negative pressure may still be created by using exhaust fans in an adequate number and capacity such that the

exhausted air is greater than the supplied air and preferably positioning the exhaust fans just above or near the head of the patient’s room.²⁸ Care must be taken that airflow direction remains from clean areas to less clean areas (inside the isolation rooms) and in no circumstances the air from less clean areas should go to clean areas like corridors (in front of the general ward/ICU).³¹

Treatment of Exhausted Air

Treatment of exhausted air from potentially infected areas (due to its high viral load) is strongly recommended. Treatment is preferably done with HEPA filters placed at the discharge end of the exhaust duct or using a virus burnout unit.²⁸ Other cost-effective options could be chemical disinfection of exhausted air using a “diffused air aerator tank,” holding a 1% sodium hypochlorite solution.^{28,31} The aeration tank should be placed in an unpopulated outdoor area and not inside an enclosed space. All adequate preventive measures (including personal protective equipment) to be taken by the maintenance staff while dealing with the disinfection. In resource-limited countries, exhausted air can be taken off through an upward plume at a height of 3 m above the tallest point of the building, thereby lowering the viral load concentrations to insignificant levels by dilution.

Temporary Negative-pressure Rooms

The concept of isolation rooms dates back to 1980 when designs were given by Andrew Streifel, a hospital environment specialist, while trying to protect immune-compromised bone marrow transplant patients at the University of Minnesota Medical Center.³² Modern isolation rooms are single-patient rooms with an adjoining bathroom and anteroom.

For mechanically ventilated hospitals, the Centers for Disease Control and Prevention (CDC) recommends that isolation rooms with airborne precaution should have the following essential features for air handling and airflow direction:³⁰

- A negative-pressure differential of ≥ 2.5 Pa (0.01-inch water gauge)
- Clean to dirty airflow
- Sealing of the room, approximately 0.5 square ft (0.046 m²) leakage
- with ≥ 12 ACH for new building and ≥ 6 ACH in existing buildings (e.g., equivalent to 40 L/s for a 4 × 2 × 3 m³ room)
- An exhaust to the outside, or a HEPA filter if room air is recirculated

Architectural changes for the creation of an airborne infection isolation room (AIIR) though desirable are difficult goals to achieve, especially in the middle- to low-income groups of countries. Permanent architectural changes are time and resource consuming. Usually, hospitals have insufficient facilities to provide airborne infection isolation for large numbers of patients with airborne infectious diseases presenting in a short-time period, leading to poor outcome and resource exhaustion.^{33–35} Temporary negative-pressure isolation rooms (TNPI) could be a way out. Figure 3 describes the construction of a temporary negative-pressure room.

Temporary structures can be designed to protect patients and staff from isolation. Learning from the past experience of respiratory pathogen outbreaks, the following are the proposed methods for structural changes that can be made to optimize recourses to build AIIRs on a temporary scale. The recent SARS-COV-2 pandemics have also shown the effectiveness of TNPI in America to deal with large-scale outbreaks of airborne diseases.³⁵

Salient Features of TNPI

Industrial exhaust fans can be used to create such TNPI. To attain the level of recommended air exchanges, the flow capacity of the fan should be 50% greater than the calculated flow requirement.³⁶ To prevent the exhaust of unfiltered gas into the environment, HEPA filters should be integrated. CDC recommends that for air exhaustion air intake ducts should be separated by at least 8 m. Separation should

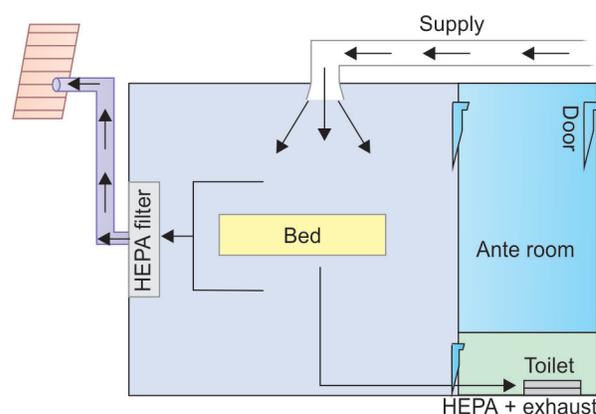


Fig. 3: Model for temporary negative pressure room

probably be greater for contaminated exhaust. It is recommended that the air changes achieved and the negative pressure inside the rooms be monitored regularly. Recirculation should be eliminated or minimized. For this, the air-conditioning system should be modified to introduce more fresh air, eliminating recirculation of gas if possible. Any recirculated gas should pass through a HEPA filter. They should remove at least 90% of particles (0.5 microns in size and larger) from outside and inside.^{37,38} Smoke test using airflow studies should be done to make sure that stagnation of air is not occurring.³⁹ Other general measures like separate entrance and exit to the contaminated areas with separate areas of donning and doffing should be ensured. Hand hygiene facilities at the entrance and exit are essential. Standard recommendations for piped gas, plumbing, and electrical outlets should be followed as failure to do so leads to unintended air leakage. This causes difficulty in controlling the airflow rates and pressure differentials.^{40,41}

A performance assessment of AIIR and TNPI was done in 2006, and the authors concluded that many hospitals are not maintaining AIIRs to correspond with the guidelines.⁴² A review on the effectiveness of AIIR was done in 2011, stating that there is a dearth of standardized country-specific guidelines in many countries. Few countries like the United States have guidelines but the availability of resources makes it difficult for the guidelines to be completely adopted, hence the variability in AIIRs across the world. Table 1 describes three models for the construction of TNPI.

Air Cleaning Technologies

Air cleaning technologies act by decreasing the indoor concentration of pathogen/pollutant. They do not completely give protection from airborne infections as only the air which passes through the cleaner is cleaned. Therefore, these technologies can be used only as a supplementary strategy. Prior to getting to identify appropriate cleaning technologies, it is important to understand the theory of air filtration technologies used for cleaning of air.⁴³ Filtration technologies have come a long way from the early days of Brownian movement of the early 19th century to the use of various kinds of filtration media to electret filtration process and the use of nanomaterials in the filtration media. A variety of filter materials, like glass fiber, superfine glass fiber, film compound filter material, electret filters, nanomaterials, etc., are used depending on the level of filtering efficiencies and target pollutant (suspended particles, volatile organic pollutants, and microorganisms).⁴⁴ Each purification technology targets different types of pollutants. Filtration, water washing purification, electrostatic

Table 1: Three standard models of temporary negative pressure isolation room

A) Use of high-efficiency particulate air (HEPA) filter and discharging air to outside
<ul style="list-style-type: none"> • Preferred method • Filter is used to exhaust air to outside • In addition to cleaning contaminated air, HEPA filter also helps in maintaining the negative pressure of the room • Flex duct is used to connect a window template and HEPA machine • Return system of the room should be sealed to prevent pulling of air
B) Use of HEPA filter and discharging air to return air system
<ul style="list-style-type: none"> • HEPA filter machine is used to discharge room air into the return air system • Discharged air is HEPA filtered, it is accepted to exhaust it through the return air system • A flex duct connects return grille adapter and HEPA machine • This return duct must be sealed to prevent pulling air from return air system • For exhausting large volumes of air. additional precautions should be taken
C) Curtain TNPI
<ul style="list-style-type: none"> • A good quality, fire-rated plastic is used and fitted all around the bed • Plastic walls should be 3 ft away from the bed and 6 inches taller than the ceiling • HEPA filter should be inserted into the plastic sheeting. The intake must be within the plastic enclosure and the output must be outside the plastic enclosure • The machine will draw the air from the room, filter it, and exhaust it to the rest of the room, helping provide an airflow that will help isolate the patient • The HEPA filter and the remaining surfaces should be sealed with a tape • Not a preferred method

precipitation, and anion technology are mainly used to treat suspended particles, of which filtration being the most commonly used technique. Activated carbon, photocatalytic, and plasma are used for treating harmful gases. For treating microorganisms, ultraviolet is the most commonly adopted technology followed by photocatalytic and plasma purification. Broadly speaking, all air cleaning technologies can be put under three broad categories—mechanical filtering, ionization, and chemical methods.

Owing to the multiplicity of air pollutants, different solution providers, therefore, combine various purification methods instead of using one treatment technique. Table 2 summarizes the various air purification techniques used by different brands. Most of the air cleaning technologies use filtration (mostly HEPA filter) in combination with one or the other technology. One of the defining criteria while selecting the air cleaning technologies is high filtration efficiency for the targeted pollutants, low pressure drop, energy used apart from installation, and replacement costs (filters). All these technological solutions come in both portable (popularly known as in-room air cleaners/filters) and nonportable (ceiling/wall/ducting/stand-alone large units) formats. Placement of such filtration technologies is also critical and should be done in consultation with ventilation engineers and infection control experts.

In-room Air Cleaners

Critical places like ICUs can enhance their indoor air quality and control infection by using in-room air cleaners and are strongly recommended if the healthcare facility has no central air-cleaning facility.⁴⁵ Healthcare facilities have varying requirements for high-efficiency filtration of airborne microorganisms to protect patients, staff, and visitors (e.g., in operation theaters, ICUs, and isolation rooms).

The Indian Society of Heating, Refrigerating and Air Conditioning Engineers guidelines on COVID-19 mention the efficacy of using portable room air cleaners with a certain level of caution.²⁸ Experts by and large agree that the use of adequate numbers of in-room air cleaners can help in reducing pollutant load when the same cannot be achieved by the regular HVAC system. Studies recommend the

Table 2: Air purification brands and application of purification techniques

Origin	Brand	Purification techniques					
		Filtration	Adsorption	Electrostatic precipitation	UV	Anion technology	Plasma
Europe	Philips	√	√				
	Blueair	√	√	√			
	Electrolux	√	√				√
	Dyson	√	√				
	IQAir	Hyper HEPA	√				
US	Honeywell	√	√				
Korea	Coway	Green Anti-flu HEPA	√				
	Samsung	√	√				
Japan	Sharp	√	√				√
	Panasonic	√	√			Nano ion water	
	Daikin	√					
	Hitachi	√					
India	Beyond Compare MATE	√	√	√	√	√	
	Advind Health	√	√				
	Magneto CleanTech	Unique filterless magnetic technology	√		√		



use of HEPA filters compared to any other combination like HEPA with ultraviolet germicidal irradiation (UVGI) lights, stand-alone UVGI lights, or the latest plasma bipolar isolation. CDC does not recommend the use of UVGI inside HEPA.³⁰

However, several of the air cleaners available in the market for healthcare sectors showed the use of HEPA with UVGI. Whatever be the chosen cleaning technology, it is pertinent to note that a strict operation and maintenance protocol should be followed for cleaning of the filters at regular intervals, depending on the climatic zone of the hospital (places and seasons with higher humidity require more frequent cleaning). It is also worth mentioning that filters installed in the air-handling units and window and wall air conditioner are often found to be sources of microbial growth and require strict implementation of adequate cleaning protocols.^{46,47} Discharge points should be located away from any air-intake points and populated spaces.²⁸ From a maintenance viewpoint, purchase of critical spare parts at the time of purchase deal is very important, as sometimes unavailability of spare parts leads to abandoning the equipment. Therefore, hospitals should maintain a spare part inventory with due importance.

CONCLUSION

An appropriately designed ventilation system plays a crucial role in the prevention of airborne infection transmission. A multidisciplinary approach with experts in hospital engineering is required to run an air quality management program in hospitals. The team should never ignore the suitability of the product for hospital type and consumer served. Though sophisticated mechanical systems are the best method to ventilate a building for the strictest control of airborne transmission, they are costly and difficult to maintain as per recommended standards. Using natural/hybrid ventilation, creating temporary negative-pressure rooms, and supplementary air cleaning technologies are feasible options in hospitals with resource limitations.

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