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Control and management of hospital indoor air quality

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Background:

The complex hospital environment requires special attention to ensure healthful indoor air quality (IAQ) to protect patients and healthcare workers against hospital-acquired (nosocomial) infections and occupational diseases. The aim here is to recommend effective guidelines for the control and management of hospital IAQ.

Material/Methods:

The authors have done an extensive literature review and conducted comprehensive IAQ assessments in nine hospitals. It is noted that the IAQ measurements are not presented in this paper because of confidentiality. However, the IAQ analysis was studied carefully in the development of the recommendations given in this paper.

Results:

The airborne chemical and microbiological contaminants of concern for hospitals have been identified and the major emission sources, monitoring methods, and exposure limits have been well documented and are reviewed here. Proper engineering system designs and operations are also reviewed, with recommendations for effective dilution and removal of the contaminants. The control and mitigation measures cover mechanical ventilation, filtration, differential pressure control, directional airflow control, local exhaust ventilation, and ultraviolet germicidal irradiation (UVGI) disinfection. Their applications in critical environments, such as operating theatres, isolation rooms, and other typical units, such as outpatient departments and laboratories, are also considered.

Conclusions:

Effective IAQ monitoring methods and mitigation measures suitable for the hospital environment have been identified. Accordingly, strategies for the implementation of a hospital indoor air quality management system are recommended. Healthcare workers, hospital engineers, and administrative staff can use the above as guidelines to manage and run their hospitals with healthful indoor air quality.

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BACKGROUND

The primary role of a hospital is to provide medical treatment and nursing care to patients. There are various healthcare facilities and departments, such as inpatient wards, operating theatres, intensive care units (ICUs), outpatient departments (OPDs), pharmacies, radiology departments, laboratories, etc. Each facility has its own functions, and the day-to-day running of each can be very different from the other facilities. The three main groups of occupants of a hospital are patients, healthcare workers, and visitors. Individual groups are different in terms of their health status and susceptibility to airborne chemicals and microbes. The diversity of facilities and occupants makes the complex hospital environment unlike that of any other commercial and industrial buildings. The control of indoor air quality (IAQ) plays an important role in the prevention of infection in hospitals to protect both hospital staff and patients, especially immunosuppressed and immunocompromised patients, who are highly susceptible to the adverse effects of various airborne chemicals and microbes. Poor hospital IAQ may cause outbreaks of sick hospital syndrome (SHS), causing headaches, fatigue, eye and skin irritations, and other symptoms. More seriously, improper control of hospital IAQ may cause hospital-acquired (nosocomial) infections and occupational diseases.

The aim of this paper is to recommend useful guidelines that facilitate the control and management of IAQ in hospitals. Effective engineering systems for applications in various healthcare facilities to aid in the maintenance of superior IAQ are presented. From the administrative viewpoint, an IAQ management system has been developed specifically for the typical organizational structure found in hospitals, including healthcare workers, engineers, and support staff.

MATERIAL AND METHODS

In this study, the authors did an extensive literature review and conducted comprehensive IAQ audits in nine hospitals. Both short-term (15-minute) and continuous (24-hour) measurements were used for thorough air sampling. After analyzing the IAQ audit results, the serious chemical and microbiological indoor air pollutants as well as their sources, adverse health effects, and exposure limits were identified. In order to achieve good IAQ fulfilling the exposure limits, effective monitoring methods and mitigation engineering measures were specified. Proper uses of ventilation and filtration methods were studied and are described in this paper. The success of hospital IAQ relies heavily on the joint efforts of hospital engineers, healthcare workers, and other staff members. Thus, special administrative strategies for the implementation of a hospital IAQ management system have been designed for the typical hospital staff organization and are given here.

RESULTS

Achieving good hospital IAQ is a challenge to both hospital engineers and healthcare workers. Healthcare workers should practice medical care with effective source control in order to minimize pollutant emission, e.g. using scavenging masks to collect waste anesthetic gas, wearing powder-free latex gloves to minimize airborne latex allergens, performing clinical diagnosis to identify infectious patients for proper isolation, etc. On the other hand, engineers should

Table 1. Exposure limits of chemical pollutants.

Reference	Glutaraldehyde (C ₅ H ₈ O ₂)	Nitrous Oxide (N ₂ O)
	ppm	ppm
UK HSE (1998) [3]	0.05 (8 hr)	–
OSHA (1992) [4]	0.2 (15 min)	–
NIOSH REL (1999) [5]	0.2 (ceiling)	25 (8 hr)
ACGIH (1994) [6]	0.05 (ceiling)	50 (8 hr)
NOHSC (1995) [7]	0.1 (8 hr)	25 (8 hr)
OSH (2002) [8]	0.2 (15 min)	25 (8 hr)

design, operate, and maintain the heating, ventilating, and air-conditioning (HVAC) systems and other engineering systems for effective dilution and elimination of indoor air pollutants. The following sections discuss the serious airborne contaminants and essential engineering mitigation measures needed in different hospital facilities.

Hospital indoor air pollutants

In commercial buildings and public places, the important indoor air parameters have been identified and are well understood [1,2]. They include carbon dioxide (CO₂), carbon monoxide (CO), nitrogen dioxide (NO₂), ozone (O₃), formaldehyde (CH₂O), total volatile organic compounds (TVOC), respirable suspended particulates (RSP), radon, and total bacterial count. These can adversely affect our health with various degrees of severity, ranging from sick-building syndrome (SBS) to building-related illnesses (BRI), such as pneumonitis and cancers.

Besides the above-mentioned airborne pollutants, there are other serious chemical contaminants of considerable concern for hospitals, including glutaraldehyde (C₅H₈O₂), nitrous oxide (N₂O), and latex allergens. Recommended exposure limits of C₅H₈O₂ and N₂O are provided in Table 1. Airborne microbial contamination and infection are also serious factors in hospital IAQ. Pathogenic microbes with diameters of 1 to 5 µm can be suspended in the air, enabling disease to be transmitted easily. Table 2 presents the sources of harmful microbes, including multidrug-resistant *Mycobacterium tuberculosis* (TB) bacteria, *Legionella* bacteria, methicillin-resistant *Staphylococcus aureus*, and *Aspergillus* spores.

Mechanical ventilation

Mechanical ventilation is essential for diluting indoor air pollutants by exhausting the contaminated indoor air and introducing clean outdoor air into an air-conditioned building. ASHRAE [9,10], AIA [11], and CDC [12] have recommended air change rates for outdoor air and total air for major healthcare facilities in terms of air changes per hour (ACH), as summarized in Table 3. The recommended outdoor air change rates are based on the quality of the outdoor air meeting the minimal standards, as given in Table 4 [10]. If the outdoor air is of poor quality, it should be treated to reduce contaminants before it is drawn into the in-

Table 2. Sources of airborne microbial pollutants.

Pollutants	Sources
<i>TB bacteria</i>	<ul style="list-style-type: none"> When an active TB patient coughs, sneezes, or speaks, airborne TB droplets will be generated.
<i>Legionella bacteria</i>	<ul style="list-style-type: none"> A common source of this bacterium in hospitals is the water mist discharged from the cooling towers and then drawn into the indoor environment through the outdoor air intake. Other probable sources include evaporative condensers, potable water systems, and hot water systems.
<i>Staphylococcus aureus</i>	<ul style="list-style-type: none"> The bacteria are present on the skin and in the nose, blood, and urine of an infected patient. During some surgical procedures that require the use of power tools, such as oscillating bone saws and bone drills, microbial aerosols will be generated.
<i>Aspergillus spores</i>	<ul style="list-style-type: none"> Hospital renovation or nearby construction work are major sources of aerosolized <i>Aspergillus spores</i>. The fungal spores from soil, plants, animals, and dust particles can attach themselves to the clothing of healthcare workers or visitors.

Table 3. Ventilation requirements.

Area	Outdoor air change rate	Total air change rate	Outdoor air requirement
	ACH*	ACH	L/s/Person
Patient room	2 [9,11]	4 [9,11]	13 [10]
Operating theatre	15 [9]	15 [9,11]	15 [10]
Intensive care unit	2 [9,11]	6 [9,11]	8 [10]
Infectious isolation room	2 [9]	6** [9,12]	–
Protective isolation room	2 [9]	15 [9]	–
Laboratory	2 [9]	6 [9,11]	–
Delivery room	15 [9]	15 [9,11]	–

* ACH refers to the number of air changes per hour for an enclosed environment;

** For newly constructed and renovated infectious isolation rooms, a higher level of protection by means of 12-ACH total air change rate should be provided [12,14].

door environment. In critical areas, such as operating theatres and delivery rooms, ventilation by 100% outdoor air is required. For areas in which the pollutant concentration is highly related to the number of occupants, the outdoor air requirements given in terms of the volume of outdoor air intake per occupant should be employed to achieve acceptable IAQ [10]. Such requirements are determined based on physiological considerations, professional judgment, and subjective evaluation. The values are also summarized in Table 3. Moreover, local exhaust ventilation by means of chemical fume hoods and biological safety cabinets should be used to control critical emission sources of contaminants in sterilizing rooms, endoscopy rooms, laboratories, tissue processing rooms, and the like.

Filtration

Filters can effectively trap particulate contaminants, including microbiological pathogens, and remove them from the circulating air. Various grades of filters can be used to achieve different degrees of cleanliness. For a healthcare facility, a

Table 4. Minimal standards for outdoor air quality.

Contaminant	Average concentration [10]		
	ppm	µg/m ³	Period
Particulates (PM10)*	–	50	1 year
	–	150	24 hours
Carbon monoxide (CO)	9	10,000	8 hours
	35	40,000	1 hour
Nitrogen dioxide (NO ₂)	0.055	100	1 year
Sulfur dioxide (SO ₂)	0.03	80	1 year
	0.14	365	24 hours
Ozone (O ₃)	0.12	235	1 hour
Lead (Pb)	–	1.5	3 months

* Particulates (PM10) refer to suspended particles having diameters of 10 µm or less.

proper filtration system generally consists of a prefilter and a final filter as shown in Figure 1. A prefilter with 25–30% dust spot efficiency should be placed upstream, ahead of the cooling/heating coil, to remove large particles for a clean heat transfer medium. More importantly, the prefilter can prolong the life of the final filter placed downstream of the air-handling unit (AHU), resulting in a cost-effective operation. The final filter should have at least 90% efficiency to collect nearly all fungal spores of 2–5 µm diameter and bacteria in colony-forming units of 1 µm diameter or larger. In a critical area serving an immunocompromised patient, a high-efficiency particulate air (HEPA) filter with 99.97% efficiency on 0.3 µm particles should be used. Ultra-low penetration air (ULPA) filters at 99.999% efficiency on 0.1–0.2 µm particles are also available. The filtration requirements for some typical hospital areas, provided by ASHRAE [9] and AIA [11], are summarized in Table 5.

Differential pressure control

Maintaining a differential pressure between two adjacent areas, such as isolation room and corridor as illustrated in

Table 5. Filtration requirements.

Area	Filter efficiency	
	Prefilter	Final Filter
Patient room	25–30% [9,11]	90% [9,11]
Infectious isolation room	25–30% [11]	90% [11]
Protective isolation room	25–30% [11]	90–99.97% [11]
Intensive care unit	25–30% [9,11]	90% [9,11]
Delivery room	25–30% [9]	90% [9]
Laboratory	80% [9,11]	–
Operating/surgical room	25–30% [9]	90% plus additional 99.97% [9]

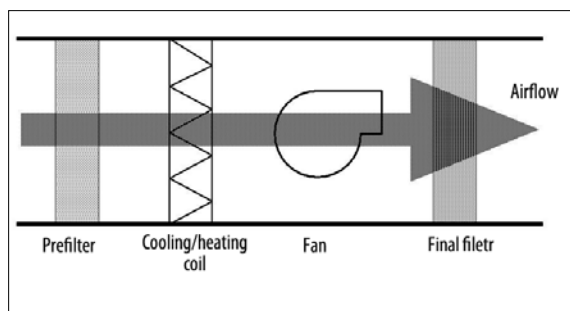
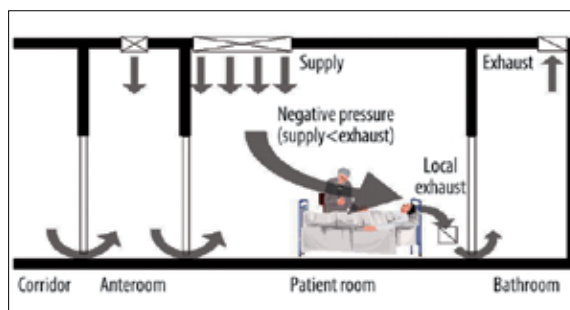
Table 6. Differential pressure control.

Area	Differential pressure
Infectious isolation room	Negative
Darkroom	Negative
Equipment sterilization room	Negative
Laboratory	Negative
Intensive care unit	Positive
Protective isolation room	Positive
Operating/surgical room	Positive
Delivery room	Positive
Pharmacy	Positive
Patient room	Equal

“Negative pressure” means the air pressure of the facility is lower than that of the adjacent areas.

Figure 2, can restrict the air leakage in a single direction through the door undercut. Thus, in order to prevent nosocomial infection, the air pressure distribution among various facilities of a hospital should be controlled to ensure clean-to-less-clean airflows. Table 6 presents the appropriate differential pressures for typical hospital facilities. The differential pressure should be at least 2.5 Pa (0.01 in. of H_2O) so that any interference due to door opening, elevator movement, and other normal activities will not change the positive or negative nature of the pressure or the airflow direction [11,13]. For a typical hospital facility that has 0.046 m² (0.5 ft²) leakage (approximately the undercut of two doors), a positive pressure of 2.5 Pa can be obtained by regulating the supply air to a level exceeding the exhaust air by 59 l/s (125 cfm) [13]. Conversely, a negative pressure of –2.5 Pa can be obtained with the supply air 59 l/s (125 cfm) below the exhaust air.

The Department of Human Services in Melbourne, Australia, recommends a different isolation room design [14]. A tight-fitting door with a door grille is used to facilitate the differ-

**Figure 1.** Configuration of filtration system.**Figure 2.** Differential pressure control in infectious isolation room.

ential pressure control. The supply air is 100% fresh air at a rate of 12 ACH. The differential pressure between the isolation room and the anteroom is maintained at least 15 Pa. The Francis J. Curry National Tuberculosis Center in San Francisco, U.S.A, also recommends another differential pressure setting equal to 7.5 Pa [15]. Maintaining a differential pressure demands constant attention to air balancing. The loading of an HEPA filter will increase the pressure drop, reduce the supply air, and thus may cause a positively pressurized room to become negatively pressurized. Therefore, regular maintenance of the filtration system should be enforced. For a critical area, a differential pressure monitoring system is recommended for continuous checking of the operating condition. More relevant details can be found in references for isolation room designs [15] and ventilation control for the prevention of nosocomial transmission of tuberculosis [16–18].

Directional airflow control

Besides air leakage between two adjacent areas, the clean-to-less-clean principle is applied to the airflow within an enclosed environment. The air movement should be from clean zones to zones of progressively greater contamination. In an operating theatre, a unidirectional (laminar) airflow should be maintained to avoid undesirable air turbulence. Any turbulence that causes mixing of airborne pathogens will increase the risk of nosocomial infection. Vertical (from ceiling to floor) and horizontal (from wall to wall) unidirectional flow methods are commonly used. A vertical unidirectional airflow, as illustrated in Figure 3, can effectively remove contaminants dispersed by the surgical team. The clean air is supplied from the ceiling vertically towards the surgical site. The supply diffusers should be of the unidirectional type. The contaminated air is exhausted to the sides at floor level. In practice, the actual

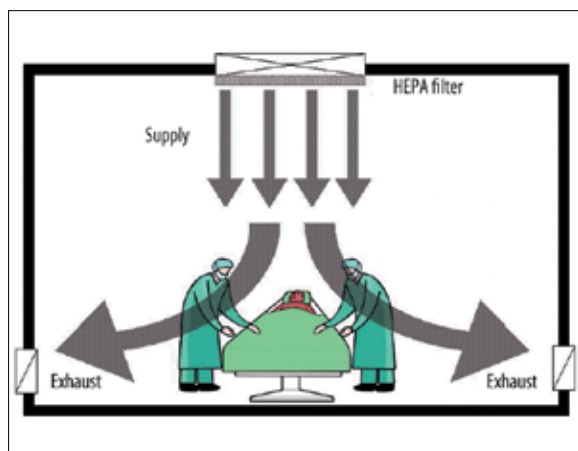


Figure 3. Vertical unidirectional airflow in operating theatre.

airflow pattern may be different from the ideal condition illustrated in Figure 3, depending on a number of factors, such as the physical environment, ventilation rate, interference by healthcare workers or surgical tools, etc. The actual airflow direction can be measured by a smoke test using chemical smoke tubes.

Ultraviolet germicidal irradiation (UVGI) disinfection

UV radiation of wavelength 220–300 nm can penetrate cell walls and inactivate tiny airborne droplet nuclei by disrupting their reproductive mechanisms [19,20]. Airborne pathogens, such as *multidrug-resistant Mycobacterium tuberculosis bacteria*, *Legionella bacteria*, and measles viruses, can be killed by UVGI [12,21]. However, UVGI is less effective against fungal spores. The efficiency of disinfection depends on both the UV radiation field intensity and the residence time of microbes exposed to the radiation field. Therefore, the mechanical ventilation system should maintain an air speed not exceeding the limit recommended by the UVGI system manufacturer for sufficient residence time. A detailed design for optimal disinfection performance can be accomplished by computer modeling methods [22]. The two typical installation configurations are shown in Figure 4. ASHRAE [9], AIA [11], and CDC [12] recommend that UVGI be used to supplement the essential engineering control methods, including mechanical ventilation, filtration, and differential pressure control, but UVGI cannot be used as a substitute for any of these methods.

Management strategy

The success of IAQ control in a hospital strongly relies on the joint efforts of the engineering, healthcare, administrative, and support staff. An IAQ management program can best facilitate the coordination of the necessary activities to identify, correct, and prevent IAQ problems. The implementation of a management program can also raise awareness in all staff for achieving good hospital IAQ. The following seven-step IAQ management program is designed for the implementation in a healthcare facility.

Step 1: Allocation of responsibilities

- Appoint an IAQ manager responsible for the overall development and implementation of the IAQ management

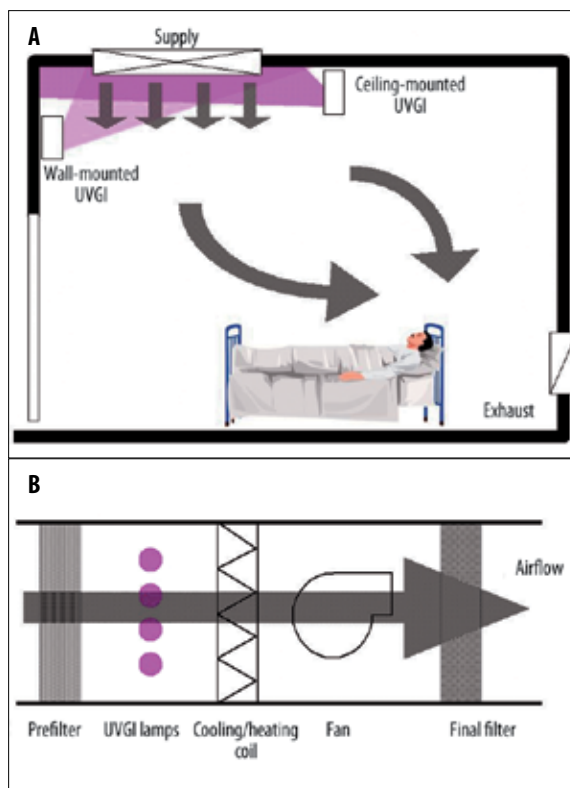


Figure 4. UVGI installation configurations: (A) Upper-room configuration and (B) Air-duct configuration.

program. The ideal candidate will be someone from senior management.

- Set up an IAQ management team comprising IAQ officers from different departments to assist the IAQ manager. A desirable organizational structure for an IAQ management team is shown in Figure 5.

Step 2: Preparation performed by the IAQ manager

- Study the literature on hospital IAQ to gain a basic understanding of the problems, control strategies, mitigation measures, and preventive actions.
- Be aware of new and existing legislative requirements, standards, and guidelines; ensure that they are fully understood by all hospital staff.
- Develop a Hospital IAQ Policy endorsed by the senior management; alternatively, the commitment to good IAQ can be defined in either the Environmental Policy or the Safety and Health Policy.
- Identify the potential IAQ problems that could be caused by healthcare procedures and equipment.
- Identify poor engineering designs and operations of the ventilation and filtration systems that may cause IAQ problems.

Step 3: Review of work contracts and procedures

- Include necessary preventive actions in the terms of contracts to remove dust and chemicals generated by construction and renovation works.
- Revise specifications as necessary for cleaning products, construction materials, furnishings, and medical equipment to achieve low emission of chemical pollutants.

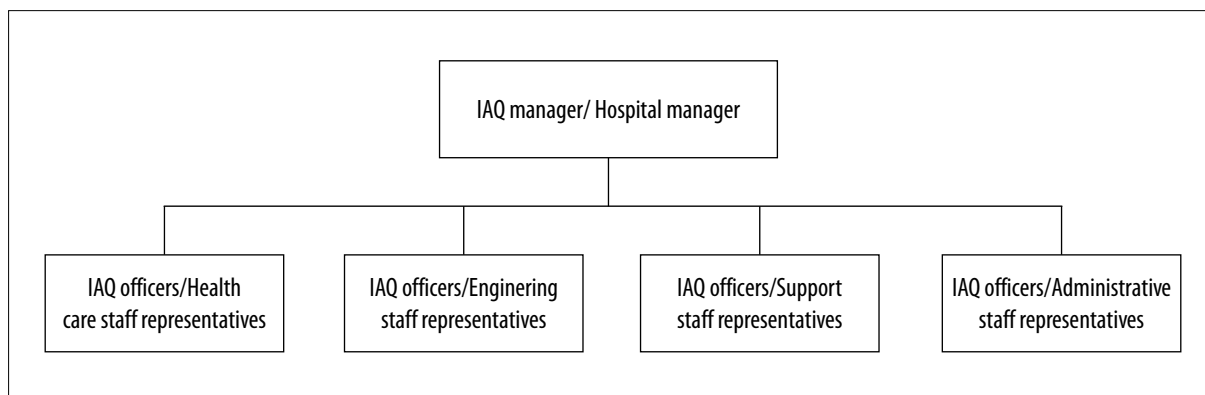


Figure 5. Organizational structure of IAQ management team.

Step 4: Review of hospital staff activities

- Ensure that hospital equipment and furnishings are placed in positions where they do not interfere with the design airflow.
- Assist IAQ assessment and investigation activities when required.

Step 5: Communication

- Document and communicate with all staff regarding issues related to hospital IAQ, i.e. chemical spillage and leakage incidents, reported SHS, reported outbreaks of infection, IAQ assessment and investigation results, recommended guidelines, etc.
- Provide a platform for receiving and responding to IAQ complaints.

Step 6: Investigation

- Conduct questionnaire surveys to collect information from hospital staff.
- Analyze the data and information collected to identify potential IAQ problems.
- Conduct periodic walk-through inspections of healthcare facilities and engineering systems.
- Conduct comprehensive IAQ assessments with detailed measurements.
- Analyze the measurements, identify appropriate mitigation measures, and implement them.

Step 7: Record keeping

- Keep records of IAQ-related complaints and follow-up actions.
- Keep records of IAQ questionnaire surveys to monitor progress and as indicators of IAQ performance.
- Keep records of walk-through inspections and comprehensive IAQ assessments conducted.
- Register all IAQ-related symptoms and illnesses reported by hospital occupants.

CONCLUSIONS

Standards and guidelines are made available in this study for effective engineering system designs, control mechanisms, and operations that fulfill the technical requirements for health-

ful IAQ in the complex hospital environment. In addition, a management program specially designed for controlling the emission sources, coordinating preventive activities, promoting staff awareness, etc. are essential, in order to provide the patients and hospital staff with maximum protection.

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