In the mid-1990s, the Australian state of Queensland undertook a major redevelopment of a significant number of the hospitals in the state. For the capital city of Brisbane, this included the construction of extensive new inpatient, outpatient and clinical services buildings. The construction program covered the majority of tertiary services hospitals serving Brisbane and the state, with most either totally or near totally rebuilt.

Hospital health care in Australia consists of a large public hospital system providing mostly free hospital services with a separate private hospital system operating on a fee for service basis. The public health system in Queensland is the largest provider of hospital services in the state and as such the Queensland Health Department oversees the largest and most diverse hospital building infrastructure in the state.

The Queensland Health Department made a decision early in the redevelopment program to develop infection control guidelines for construction and refurbishment. The guidelines titled “Building and Refurbishment—Infection Control Guidelines” were first published in 1997, and the current revised version released in 2002. The guidelines, although containing many relatively standard practices including consolidation of design requirements, was one of the first guidelines relating to actual during-construction practices published in Australia. The guidelines included a specific operating room ventilation design which was subject to computational fluid dynamics (CFD) analysis in the decision process. The guidelines also have been applied to private hospitals in the state, via state legislation that covers development and construction of private hospitals.

The Guidelines
The guidelines cover infection control in construction from a number of perspectives including:

- Basic principles and intent;
- Project planning and consultation;
- Construction practices; and

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• Design, covering both functional planning requirements such as number and location of hand basins as well as more fundamental aspects such as air conditioning filter selection.

The term nosocomial infection is applied to infections which are acquired and transmitted by patients within a hospital. By way of indicating the extent and effect of nosocomial infections, The New England Journal of Medicine article “Infection control—a problem for patient safety” stated (in relation to the U.S.):

Currently, between 5 and 10 per cent of patients admitted to acute care hospitals acquire one or more infections, and the risks have steadily increased during recent decades. These adverse events affect approximately 2 million patients each year in the United States, result in some 90,000 deaths, and add an estimated $4.5 to $5.7 billion per year to the costs of patient care. Infection control is therefore a critical component of patient safety.²

An organism that has no adverse effect on a healthy individual may be life-threatening to an ill patient suffering with a suppressed immune system due to a preexisting medical condition or medical treatment. Likewise, during surgery the procedures expose areas of the body, normally protected, to attack from multiple sources of infection.

Part of the management to prevent infections, therefore, requires provision of buildings that provide:

• Barriers to infection transmission within the facility and from external sources;
• Functional layouts that reduce opportunities for infection transmission;
• Hygiene services to staff and patients for minimization of transmission risk;
• Minimum opportunities to harbor infectious organisms; and
• Facilities that can be readily cleaned and disinfected.

Added to this are the management practices and procedures undertaken by the health-care professional and support staff.

Key areas in relation to HVAC covered in the guidelines include infection control during construction, general design considerations and specific design requirements for areas such as isolation rooms, operating rooms, etc. The development of these HVAC aspects resulted from a mixture of existing general government requirements on health projects, research on health projects, research of other published text, articles, papers and
guidelines, some validation research and advice from health professionals specializing in infection control.

Infection Control During Construction

The actual practices and procedures during construction were identified as a major risk of introducing pathogens and/or providing suitable habitats for their propagation. The guidelines include requirements for cleaning during construction and cleaning maintenance, as well as exclusion of weather and water entry. These general requirements have in response created some prescriptive requirements in the guidelines, with the most significant being:

- Ensuring ductwork is clean both internally and externally. Ductwork is typically fully protected with covers during transport and storage with all open ends of installed duct provided with temporary end covers. The temporary covers are usually plastic sheeting taped on, with all ductwork inspected prior to erection and internally cleaned if required;
- Similar practices are used for air-handling plants and other air-system components;
- A full cleaning of all systems and concealed spaces before being closed, including riser shafts, walls and ceilings, so that the completed installation has all rubbish, dirt and dust removed;
- Where construction work is within or adjoining existing health facilities, barriers are required to prevent dirt and dust travelling to non-construction areas. In addition, filtered air exhaust is required to the construction area so that it is at a negative pressure compared to adjacent areas. The exhaust typically is filtered since the discharge to outside is frequently located at or above an external congregation area or pedestrian trafficked area of the hospital; and
- Added to this is a general requirement that all construction projects implement; control, inspection and reporting systems, which are specific to the project.

Requirements and general philosophy are given for construction adjacent to areas remaining occupied and increased vigilance is stressed for construction in relation to high-risk areas such as critical care, immunosuppressed patients (oncology, transplant wards, etc.) and respiratory disease areas.

The previous requirements would appear to be common sense for construction. However, evidence of outbreaks of nosocomial aspergillosis (aspergillosis is a commonly occurring fungus in the environment and typically only infects persons already weakened by some other medical condition) was found in various literature, where the actual construction work was found to be the cause of the outbreak. Of the research papers and textbooks reviewed in developing the guide, one text listed 12 instances of nosocomial aspergillosis outbreaks within the United States between 1974 and 1989, affecting 95 individuals, with the most common cause identified as infection resulting from renovation construction works.\(^3\)

Figure 1: Operating room—sectional view of air-distribution system.

General Design

The general HVAC design requirements include a mix of design principles and a number of specific requirements. These requirements relate only to issues relevant to infection control, as the guidelines are not intended to be a design manual for health facilities beyond those aspects considered issues for infection control.

Fundamentals of the general requirements are:

- Minimization of moisture and water in air-handling systems, with measures to prevent carryover and constant high (>80%RH) humidity in ductwork;
- Prohibited use of water bath and spray type humidifiers;
- Positive pressurization of patient areas;
- Minimum outside air rate of 2 L/s per m\(^2\) (0.4 cfm/ ft\(^2\)) of treatment/ward areas. Note that this is a minimum and code requirements may mandate an increased rate in some specific areas;
- Use of ceiling plenums not permitted with all air transport to be via ductwork.
- Supply and return air ductwork requirements include:
  - No internal linings;
  - Reasonable access provision to allow internal cleaning;
  - Attenuators to have impervious linings, typically a high strength plastic membrane; and
  - Lint screen filters on return air grilles. This was as a result of high lint levels found in the return air of existing systems. The lint was obviously from hospital washed garments as the particular colour used by different hospitals was evident in the lint found in the ductwork;
- Good access for checking, maintenance and cleaning of air-handling units. Typically requiring plant room mounted air-handling units with good access for routine maintenance and repairs; and
- Filter requirements are specified, ranging from high-efficiency particulate air (HEPA) for operating rooms and high efficiency for critical care areas to general efficiency for general wards.
Designing HVAC systems that incorporate the previous has not been difficult, except in relation to providing adequate noise attenuation in-duct. The exclusion of acoustically absorptive duct linings has increased the need for attenuators. However, added attenuator impervious linings has resulted in selected attenuators being longer in length and sometimes increased perimeter. Added to this, the requirement for reasonable cleaning access dictates attenuator installation locations that may be difficult to accommodate.

The net result has been an increase in required mechanical plant room space to accommodate the attenuators. In plant rooms with multiple air-handling units and subsequently many attenuators, special consideration has been required to achieve a well-coordinated arrangement as well as mounting and support for the increased attenuator requirements.

Other than the previous issues, compliance with the general design requirements has been relatively straightforward on health projects since their inception.

Two areas specifically dealt with in the guidelines are isolation rooms and operating rooms. For these two important areas there are specific requirements for design and construction, including HVAC requirements.

Isolation Rooms
The isolation room requirements cover both positive and negative pressure rooms, with the guideline precluding rooms that can be switched between positive and negative. Thus, designated negative pressure room is designed and always operates as a negative pressure room, with a positive pressure room designed and always operated as a positive pressure room.

Key design features include:\(^4\)\(^5\)

Positive Pressure Rooms
- Positive pressure achieved by a 10% excess of supply air from a dedicated air-handling unit;
- Pressure differential gauge for visual check by staff;
- Warning system with pressure monitoring for rooms where briefed by the client hospital as critical;
- Warning alarm on system failure; and
- 12 air changes per hour on supply air as a minimum with recirculation permitted and a minimum outside air rate as per code.

Negative Pressure Rooms
- Negative pressure achieved by 10% excess of exhaust airflow;
- All outside air single-pass air systems;
- Dedicated air handler per room. However, grouping of rooms is permitted with separate exhaust per room;
- Special requirements on exhaust system, including high level air discharge and warning notices to maintenance personnel;
- 12 air changes per hour on supply air as a minimum;
- Pressure differential gauge and warning alarm on loss of pressure and system fault; and
- Exhaust system not required to be filtered, except in situations where briefed by the hospital as requiring such provision.

Operating Room
Obviously, infection control in the operating room environment is the most challenging as the nature of surgery provides significant infection risk. The other aspect of surgery is that infections will be internal and difficult to treat. This is compounded by increasing numbers of multi-resistant organisms occurring in health care facilities such as methicillin-resistant staphylococcus aureus (MRSA) “golden staph” and vancomycin resistant enterococcus (VRE).

Hence, the operating room is a unique area, even within a hospital in terms of the risk factors for a patient. Sources of infection are multiple, including:
- The patient, self infection into the body from the patient’s skin flakes and other particles on the body;
- The operating room staff, from skin flakes, expired air, hair, etc.;
- The surgical instruments, wadding, etc. used in the procedure;
- Clothing worn by operating room staff;
- The room and equipment used in the room;
- Air supplied to the room; and
- Infiltration air.

The HVAC systems within Queensland hospital operating rooms, built in the 1970s, were generally of the all-outside air...
type with HEPA or medium efficiency particulate air (MEPA) filters mounted either as terminal or at the air-handling unit and air change rates of approximately 12 per hour. Air supply to the room varied between ceiling diffusers and wall mounted side blow. In the 1980s and early 1990s, the design parameters became recirculation with approximately 50% outside air, terminal ceiling mounted HEPA filters and an air-change rate of 20 per hour. Prior to the release of the guidelines in 1997, this was a common standard for Queensland government hospitals.

A literature search was conducted to identify the then-current practices, standards and research relevant to operating room HVAC. A vast amount of material was uncovered, with the major sources from the U.S., U.K. and some Australia. The material covered, ranged from full research to more speculative considerations, but few offered a recommended solution. However, a number of papers showed a common direction and a few making firm recommendations.

The favored solutions appeared to be generally either a full laminar flow or a modified version using a smaller area of filters and lower airflow. From this research, it was decided that the preferred solution was an adopted simple and small scale laminar flow style of system. The basics of the arrangement being the use of four 1200 mm by 600 mm (4 ft by 2 ft) HEPA laminar flow style of system. The basics of the arrangement being the use of four 1200 mm by 600 mm (4 ft by 2 ft) HEPA filter units ceiling mounted directly above the operating table. Basic arrangement being:

- The HEPA units are arranged to provide a square donut, with the center of the donut left for mounting lights or light/pendant combinations;
- Exhausts are located at low levels;
- Return air as a combination of low level and ceiling-mounted, with a 50/50 split between low and high level return air. The low level exhaust and return acts as collectors of particulates, with ceiling return air provided to return warm air at the ceiling. The use of linear slot grilles was with the intent to create a more even spread of air intake to prevent producing disturbing currents and to also act as a barrier to entrainment air by drawing in air before it could cause a recirculating pattern. Validity of these assumptions was not verified by analysis or in CFD modeling;
- A short drop skirt (Figure 1) as an option also was included as this was considered to potentially improve overall performance by effectively lowering the discharge point and reducing the possible effects of infiltration into the discharge airstream. This is an arrangement often used in full laminar flow systems installed to operating rooms; and
- Airflow rate set at 1700 L/s (3,600 cfm), air-change rate was not referenced, as 20 air changes per hour would always be exceeded with anticipated operating rooms sizes. Figures 1 and 2 show the basic arrangement for this system. It was decided that an obvious high confidence existed in the air quality from the HEPA filter bank and the ability to provide suitable temperature control. However, the higher air quantity above that required for normal sensible temperature and humidity control requires special consideration at the air-handling unit, depending on the prevailing local climate.

Three key factors were considered to require further investigation to achieve the necessary confidence to implement the design into the guidelines. These were:

- Room air was not entrained into the clean airstream, which may increase particulate occurrence at wound site;
- Air velocity at wound site would not exceed 0.2 m/s (39 fpm). Air velocity at wound site based on research data suggested this should not exceed 0.2 m/s (39 fpm), so as to ensure excessive drying at the wound did not occur; and
- Airflow pattern that directed first air (direct from HEPA filters) to the patient and spilled away from patient. The requirement of spill away from the patient is to provide protection from particulates from the operating room staff.

To investigate these key factors, CFD was chosen as the most appropriate tool. In conducting the CFD modeling, it was decided to exclude the influence of operating room lights, staff and equipment. While all of these items will have an undoubted effect (especially lights), variability of their size and location is too numerous to take into account. It also was considered that this simplified model would provide adequate indicative results for the purpose of investigating the three key factors.

The results of the CFD modeling were positive and supported the use of the proposed system. The basic results against the key investigation factors were:

- No significant entrainment of room air;
- Operating table (patient/wound) air velocity was below the 0.2 m/s (39 fpm) criteria; and
- First air was delivered to operating table (patient) and the airflow pattern was definitely outward, traveling away from patient.
Based on these CFD modeling results, the decision was made for this design to be included in the infection guidelines. Figure 3 shows the airflow pattern and velocity output analysis from the CFD modeling.

Since the guidelines were introduced in 1997, other organizations and individuals have carried out further research and investigation. Two papers of interest that indicate support for the design contained in the guidelines and of distinct interest are:

- “Comparison of operating room ventilation systems on protection of the surgical site.” 10, 11 This paper is of particular interest as it is an analytical study using airflow modeling to compare different ventilation system types for supplying air into and exhausting air from the operating room.
- “Comparative CFD analysis of hospital ward ventilation systems on reducing cross infection rates.” 12 This paper includes a more extensive CFD study of an operating room with a design very similar to that contained in the Queensland Health “Building and Refurbishment—Infection Control Guidelines.” The results of the CFD study, although only examining this one arrangement, support the design in the guidelines.

Since the introduction of the guidelines in 1997, many facilities have been designed and built, and practical experience has been gained. The experience gained from the design, construction and operation of these facilities has revealed the following:

- The guideline airflow rate of 1700 L/s (3,600 cfm) was found to generate excessive noise. Reduction to not less than 1500 L/s (3,180 cfm) has proven to solve the noise problem;
- Simple smoke testing with smoke pencils at commissioning using 1500 L/s indicated performance in terms of airflow pattern comparable to the CFD modeling results;
- The detailed fitment of the four HEPA filter modules and center support light/pendant requires careful consideration and detail design. This is due to the individual components requiring mounting structure and the mounting unit for a combination surgical light and services pendant can result in an area with clustered mounting units and support framing all sharing a common zone;
- Skirts to the filter group have rarely been used as surgical lights, and services pendant units have made the use of skirts difficult or impossible in many cases;
- Airflow velocity grids (measuring total airflow rate) commonly are used in supply air duct to enable airflow rate to be maintained constant as filters load, which also operates to maintain pressure regimes for infection control between operating room and other areas; and
- Local recirculation fans have not been used due to difficulties with noise and maintenance access. The experience with operating room laminar flow units in Queensland was not good in terms of acoustic performance, with strong surgeon complaints of unacceptable noise levels.

The source of the excessive noise was from local recirculation fans for the laminar flow filter units. The access to the recirculation fans for maintenance required trade staff entering the operating room or operating suite area, which was considered undesirable for hygiene reasons.

References