The ventilation of multiple-bed hospital wards in the tropics: A review

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**ABSTRACT**

Hospital and healthcare facilities have diverse indoor environment due to the different comfort and health needs of its occupants. Currently, most ventilation studies revolve around specialised areas such as operating rooms and isolation rooms. This paper focuses on the ventilation of multiple-bed hospital wards in the tropical climate, taking into account the design, indoor conditions and engineering controls. General ward layouts are described briefly. The required indoor conditions such as temperature, humidity, air movements and indoor air quality in the ward spaces are summarized based on the current guidelines and practices. Also, recent studies and engineering practices in the hospital indoor environment are elaborated. Usage of computational fluid dynamics tools for the ventilation studies is discussed as well. As identified during the review, there is an apparent knowledge gap for ventilation studies in the tropics compared with temperate climates, as fact studies have only been published for hospital wards in countries with a temperate climate. Therefore, it is highlighted that specific tropical studies along with novel engineering controls are required in addressing the ventilation requirements for the tropics.

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1. Introduction

Hospital and healthcare facilities have diverse indoor environments due to the varying needs of patients and healthcare workers. The indoor environments range from a simple general room to an operating room. Furthermore, the recent pandemic of influenza creates the maximum likelihood for airborne transmission by congregating communicable and vulnerable individuals in healthcare facilities.

At this time, ventilation in healthcare facilities is important as it provides thermal comfort and protection from harmful emissions or airborne pathogenic materials to both patients and healthcare workers [1]. Typically, the ventilation requirements for spaces are governed by building codes, regulations and specific guidelines furnished by the local health authorities and others [2–5]. These requirements vary by country, depending on the geographic location, economic background and the country's specific needs.

The benefits of environmental control for isolation wards and operating room theatres have been recorded and analysed thoroughly. However, there is a lack of ventilation studies on open ward facilities, which is where most patients are placed, especially in the tropics. Recent outbreaks of pandemic diseases have heightened the risks associated with these facilities. Thus, in this paper, the current state of knowledge of the ventilation of multiple-bed hospital wards is reviewed.

2. Ventilation in healthcare facilities

By and large, the purpose of ventilation in any occupied space is to provide fresh air to the occupants and remove heat generated within a confined space. In healthcare facilities, the ventilation system should also help prevent diseases and treat patients.

Research has shown that the design characteristics of a health-care facility, which include ventilation and layout improvements, can enhance the health outcome of the patients and provide a better working environment for employees [6]. Therefore, overall health-care quality can be partly enhanced by improving the ventilation.

Many reports have shown that infectious diseases occur due to airborne transmission and surface contaminations by droplet nuclei. This topic is further elaborated in Section 6. Transmission of Severe Acute Respiratory Syndrome (SARS) has been documented in different circumstances and locations worldwide and is found to be highly communicable in healthcare settings [7,8]. Airborne transmissions are not only limited to the SARS episode but also extend to nosocomial infections, which are more prevalent in
healthcare settings, such as open wards and intensive care units [9,10]. Apart from this, ventilation systems were also identified as a source of infection; in some cases, the systems were harbouring infectious pathogens [11,12].

Recent literature has established a relationship between ventilation and health outcomes. In 2006, an interdisciplinary panel consisting of experts in medicine, epidemiology, toxicology, environmental chemistry, aerosol sciences, psychology, engineering and architecture reviewed the effects of ventilation on health in non-industrial indoor environments [13]. The group judged that 27 of the total 365 papers studied concurred that ventilation rates are associated with sick building syndrome (SBS), especially in offices. Furthermore, the group also highlighted the need for ventilation and health studies in warm and humid climates and polluted and public localities. Moreover, a list of 40 studies between 1960 and 2005 were appraised by another multidisciplinary panel. Subsequently, they also recognised that 10 studies have put forward substantial facts that show the relationship between ventilation and proliferation of infectious diseases, such as influenza and TB [14].

Healthcare workers, such as doctors, nurses and others, are exposed to infectious diseases and demanding work conditions in healthcare settings [7,15]. Cases of transmission of contagions from patients and surface contaminations have been recorded. The risk of transmission is also increased by various environmental factors. Guidelines indicating the risks and control measures have been compiled in [2]. Several other studies have deliberated the risks of SBS in the healthcare environment, which are compiled in the 2003 Guidelines for Environmental Infection Control in Healthcare Facilities by the US Centers for Disease Control and Prevention (CDC) and the Healthcare Infection Control Practices Advisory Committee (HICPAC) [6].

Briefly, ventilation in healthcare facilities has a profound effect on the well-being of patients and employees in healthcare facilities. Thus, this paper focuses on the ventilation of multiple-bed hospital wards, including the design, indoor conditions and engineering controls.

3. General design

Multiple-bed hospital ward is a generic term used to describe the concept of a non-partitioned area that contains several beds for patients who need a similar kind of care at a healthcare facility [16–18]. The number of beds in a ward differs from one facility to another. Therefore, the configuration of a multiple-bed hospital ward can range from 2 people per ward up to 30 people per ward in many localities, including Malaysia. Additionally, it is not uncommon to subdivide the ward into multiple units that hold 4 patients or up to 6 patients. Another practice is to have 1 patient per room as stipulated in [5], which is particularly common in the United States. However, multiple-bed configurations with defined limitations are allowed for the intensive care unit and critical care unit. Compared with other clinical spaces such as operating rooms and isolation rooms, which are studied thoroughly, the aforementioned spaces are limited to one person and a few healthcare workers, such as doctors and nurses. Depending on the activities conducted and the affected floor area of a ward, these spaces are much more constrained compared with operating theatres. Furthermore, multiple-bed hospital wards require lower capital expenditure, which is why they are more widely used in developing countries compared with single-patient rooms.

Basic ward design principles revolve around lighting, ventilation and cleanliness [19,20]. The ward environment should be focused on the needs of patients and staff [21,22]. Recent studies have implied the significance of meaningful and varying stimuli (odourless and pleasant experience) in a ward environment, suggesting links between physical environments to patients’ health outcomes. These conclusions support the idea that poorly designed or maintained hospital wards may displease patients and thus promote sickness in patients rather than assist the healing process [6].

Typically, the following are the four types of hospital ward designs being utilised throughout the world [16,18,22]: bay wards (Fig. 1), nightingale wards (Fig. 2), racetrack wards and hub and spoke units. The nightingale wards have beds along the perimeter of the space, with the nurses’ station located centrally. This allows the nurses to maximise their supervision of patients. This type of ward caters up to 30 adults or 24 children and is still widely used in many developing countries. Bay wards have a central nurses’ station and cubicule rooms, which house several beds. Racetrack wards are a variant of the bay wards as they have a different arrangement for the nurses’ station and beds. The hub and spoke units have the central nurses’ station as a hub and large rooms as radiating spokes.

Nursing activities and patient welfare are also influenced by ward designs [23]. Overall, racetrack wards have higher nursing quality scores (80%) and the lowest bed cost (£54), compared with other types of wards.

4. Tropical climate characteristics

Tropics are regions on earth by the equator between 23.5° North latitude and 23.5° South latitude. Temperatures are above 18 °C and with high precipitation throughout the year. Tropical climate is further subdivided to tropical savannah, tropical monsoon and tropical rainforest, distinguished by the amount of precipitation. Seasonal changes in the tropics are dominated by
highlighting the associated risks [9,15]. Table 2 shows the main airborne diseases for humans.

Tang et al. [51] reviewed and elaborated on the aerosol transmission of infectious agents, the associated diseases and the control methods. It was pointed out that droplets are generated during talking, sneezing and coughing. Subsequently, these droplets lead to a generation of infectious agents or pathogens. The agents are able to transmit infections over short distances and in close contact. Large droplets become smaller through evaporation, causing outbreaks over larger areas. However, the susceptibility of an individual to be infected depends on the pathogen quantity exposed and their bodies’ resistance.

Weber and Stilianakis [56] reviewed the inactivation of influenza A viruses in the environment and its modes of transmission. The inactivation of influenza A viruses depends on many factors, such as relative humidity, temperature and UV radiation. From this review, the airborne mode is a significant transmission route for nosocomial infections in indoor spaces.

8. Numerical method

The advent of computational fluid dynamic (CFD) technology has provided a significant tool for comprehensive airflow analysis of an entire room [32,43,57–59]. The analysis is achieved by numerically solving a set of partial differential equations representing the conservation of mass, momentum, energy, pollutant concentrations and turbulent quantities. The followings are the three groups of basic equations that govern the numerical solution for the thermal comfort and pollutant dispersal in a space: the continuity equation, Navier–Stokes equation and energy equation. These equations can be solved by specifying the initial and boundary conditions. CFD modelling results can be shown through user friendly graphical tools. The accuracy of CFD modelling results must be verified by comparison with field data.

Generally, the airflow in healthcare premises is turbulent. Most CFD solutions predict turbulence with modelled transport equations for the turbulent kinetic energy ($k$) and its dissipation rate ($\varepsilon$), which is known as the $k$–$\varepsilon$ model. The standard $k$–$\varepsilon$ model is easy to program, numerically robust and reasonably accurate. Apart from the $k$–$\varepsilon$ model, other CFD models include the re-normalisation group (RNG) $k$–$\varepsilon$ model, Reynolds averaged Navier–Stokes (RANS) equations, Reynolds stress viscous model and large eddy simulation. More information on CFD theories and their applications can be found in [58,59].

Philips et al. [43] analysed different ventilation systems of isolation rooms using CFD models and suggested the provision of an anteroom for contagious patients. Similarly, Cheong and Phua [59] examined the airflow and pollutant dispersal profiles for a “negative pressure” isolation room through experiments and CFD simulations. Three airflow schemes were investigated, and the results suggested that airflow schemes and furniture layout influence the airflow pollutant distribution. Beggs et al. [50] performed a CFD simulation using a standard $k$–$\varepsilon$ model to explore the effect of airflow direction on the bio-aerosol concentration generated in a ward space. The results showed a significant variation between the ventilation strategies employed. It was concluded that a ceiling diffuser ventilation scheme is the most effective, improving the pollutant removal efficiency up to a 5 times. Qian et al. [8] integrated the Wells-Riley equation in a CFD model to predict the spatial infection risk distribution in a hospital ward, and the findings concurred closely with the infection distribution profile among the exposed students and patients.

The above studies represent only a small amount of research that utilised CFD tools. To evaluate the comfort levels and pollutant removals, CFD tools are very helpful in determining the sufficiency of the current design and future improvements. Furthermore, CFD tools will save much time, effort and cost prior to a facility’s construction.

9. Conclusions

Ventilation in a ward needs to be favourable to occupants (patients and healthcare workers). The ventilation should also assist in preventing diseases and treating patients. Many studies have elaborated on the health benefits of ventilating wards and its intricacies. In this review, challenges in a multiple-bed ward environment have been identified and elaborated on. However, specific problems in the tropics need to be the focus in future works as there is a lack of tropical studies.

Indoor conditions in wards are very different compared with other environments, such as an office space. These conditions affect the well-being of patients and the transmission of infections. Engineering controls employed in healthcare settings differ in terms of parameters and needs. As identified during the review, there is an apparent knowledge gap for ventilation studies in the tropics compared with temperate climates, as fact studies and guidelines have only been published in countries of temperate climates.

A mechanical ventilation system significantly helps to improve the indoor environment. Also, natural ventilation is being explored to improve the indoor environment quality. Mixing ventilation and displacement ventilation are the most prevalent principles used to design ventilation systems, which when combined with other engineering controls, such as filtration and UVGI, can significantly

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**Table 2**

<table>
<thead>
<tr>
<th>Airborne pathogen</th>
<th>Disease</th>
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<tbody>
<tr>
<td>Adenovirus</td>
<td>Colds</td>
</tr>
<tr>
<td>Arenavirus</td>
<td>Haemorrhagic fever</td>
</tr>
<tr>
<td>Coronavirus</td>
<td>Colds</td>
</tr>
<tr>
<td>Echovirus</td>
<td>Colds</td>
</tr>
<tr>
<td>Morbillivirus</td>
<td>Measles</td>
</tr>
<tr>
<td>Influenza</td>
<td>Flu</td>
</tr>
<tr>
<td>Parainfluenza</td>
<td>Flu</td>
</tr>
<tr>
<td>Parainfluenza</td>
<td>Mumps</td>
</tr>
<tr>
<td>Parainfluenza</td>
<td>Mumps</td>
</tr>
<tr>
<td>Pneumococcius</td>
<td>Mumps</td>
</tr>
<tr>
<td>Respiratory Syntical Virus</td>
<td>Pneumonia</td>
</tr>
<tr>
<td>Rhinovirus</td>
<td>Colds</td>
</tr>
<tr>
<td>Togavirus</td>
<td>Rubella</td>
</tr>
<tr>
<td>Varicella-zoster</td>
<td>Chickenpox</td>
</tr>
<tr>
<td>Chlamydia pneumonia</td>
<td>Pneumonia, Bronchitis</td>
</tr>
<tr>
<td>Mycobacterium tuberculosis</td>
<td>TB</td>
</tr>
<tr>
<td>Yersinia pestis</td>
<td>Pneumonic plague</td>
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</table>

**Table 3**

<table>
<thead>
<tr>
<th>Room type</th>
<th>Minimum hourly ventilation rates</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>General wards</td>
<td>60 l/s per patient</td>
<td>Applies for any other patient care area such as corridors where emergency care is undertaken.</td>
</tr>
<tr>
<td>Airborne precaution rooms</td>
<td>160 l/s per patient</td>
<td>Only applicable for new facilities and major renovations.</td>
</tr>
<tr>
<td>Corridors</td>
<td>2.5 l/s per m^3</td>
<td>For spaces without fixed number of patients.</td>
</tr>
</tbody>
</table>
improve the indoor environment. These systems need further optimisation for tropical conditions. CFD modelling is a valued tool for analysing airflow and evaluating ventilation systems. Recent reviews have focused on specialised clinical areas, such as operating rooms and isolation rooms. Different conditions have been simulated and verified with field measurements. However, specific studies are needed for multipled ward to bridge the knowledge gap regarding the thermal comfort, pollutant removals and transmission risk of airborne diseases. These studies along with novel engineering controls will assist in identifying the ventilation requirements for the tropics.

References

[47] Cheong KWD, Phua SY. Development of ventilation design strategy for improving the indoor environment. These systems need further optimisation for tropical conditions. CFD modelling is a valued tool for analysing airflow and evaluating ventilation systems. Recent reviews have focused on specialised clinical areas, such as operating rooms and isolation rooms. Different conditions have been simulated and verified with field measurements. However, specific studies are needed for multipled ward to bridge the knowledge gap regarding the thermal comfort, pollutant removals and transmission risk of airborne diseases. These studies along with novel engineering controls will assist in identifying the ventilation requirements for the tropics.