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Airflow patterns through a sliding door during opening and foot traffic in operating rooms

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ABSTRACT

It is common practice for operating rooms (OR) to have more pressure than the adjacent enclosures. This is to prevent the entry of potentially contaminated air and the consequent risk of wound infection. However, when the OR door is opened the pressure difference between the two areas disappears and can cause containment failures. If a person enters or leaves the OR during door operation, additional perturbations are also generated in the airflow pattern in the doorway. In this paper, instantaneous airflows are measured during the passage of a person through a sliding door in a real OR with the HVAC system working under operating conditions. An ultrasonic anemometer that measures the magnitude and direction of the instantaneous air velocity in the doorway is used. Results show that, even though the OR has a sliding door and an initial overpressure of 20 Pa, together with what is, a priori, a good HVAC system control strategy, a small volume of air enters the OR during a cycle of door opening and closing even without the passage of a person. Furthermore, if a person walks through the door the volume of air entering the OR is higher, especially if the person enters the OR.

1. Introduction

Surgical site infection (SSI) can cause significant postoperative complications. In addition to the inestimable human cost, the financial cost of these infections to hospitals and public or private health systems is considerable. While some infection risk factors are inherent to the patient, there are many preventive actions that can be taken to reduce infection rates during surgery. Some of these preventive measures are related to the HVAC system of the operating room (OR) and neighbouring enclosures.

The indoor air system of any enclosure must provide a conveniently filtered given airflow under appropriate temperature and humidity conditions. However, in the case of an OR, one of ventilation system's main tasks is to minimise deposition rates of airborne pathogen carriers into the surgical wound. This requires two additional functions in the ventilation: on the one hand, keeping the OR overpressured compared to adjacent areas so as to prevent entry of air from these areas, and secondly to provide an airflow pattern that is suited to the OR.

Concerning overpressure, a positive pressure is reported in most international standards [1]. Regional guidelines establish a positive pressure of 20 Pa with regard to adjacent spaces [2]. To achieve this overpressure, a difference between the airflow supplied to the OR and the extracted flow should be fixed. This airflow difference will depend on the sealing (air tightness) of each enclosure. Hayden et al. [3] developed an empirical model to describe the relationship between airflow difference, pressure differential and leakage area.

As for airflow pattern, there are two main alternatives: mixing (also called turbulent) ventilation, and unidirectional (also called laminar airflow) ventilation. Laminar airflow ventilation (LAF) is recommended for ORs designed for operations with a higher risk of infection, such as orthopaedic surgery or organ transplantation. In an OR with vertical LAF ventilation, clean air is supplied directly onto the operating table and its surrounding area.

- Within the area covered by the laminar airflow there are lamps, health care worker (HCW) and medical equipment. The wake under the surgical lamps [4] and the thermal plumes over the various heat sources [5,6] have a periodic and oscillating nature that alters the laminar airflow around the operating table.
- The movement of objects and people inside an enclosure plays an important role in indoor airflow dynamics and pollutant dispersion [7–11]. When entering the protected OR area of the

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unidirectional flow, a HCW drags air from the less clean area into the protected area [12]. The periodic bending movement of surgical staff also disturb the unidirectional airflow field [13].
- Finally, overpressure is lost and the airflow pattern is altered when a door is opened. If, in addition, a HCW passes through the door, their movement causes added disturbance, which differs depending on whether they are entering or exiting the OR. In either case, there is risk of environmental contamination in the OR due to air entering from the other enclosure. Such transitory events are the focus of analysis in the present work.

Several studies show that an increase in the number of times the door opens increases postoperative SSI rates [14,15]. OR foot traffic has a strong negative impact on the OR environment [16,17], even in LAF ventilated ORs [18]. Several studies report over 0.60 door openings per minute during surgery [18,19] even in a total joint replacement procedure, which is perhaps the model aseptic operating environment [14]. Andersson et al. [17] noted that 30% of door openings are unnecessary in relation to patient safety and the ongoing procedure and Panahi et al. [19] report that 47% of HCW entries into the OR had no purpose and could easily have been avoided. Furthermore, most of the “necessary” door openings are to request information and could easily be accomplished by using the telephone, electronic reporting, completion of operation data, or even by “checking a case” through the window or on a closed-circuit, real-time OR video monitoring system rather than physically entering the room [14]. Door-opening during operations is virtually inevitable, yet actions must be taken to minimise the risk of area contamination.

Airflow through the doorway may be caused by different effects: pressure difference due to the ventilation system, density difference due to temperature difference, and staff traffic through the door. In the case of hinged doors, there is an additional and important effect, namely the pumping action of the door swing [20]. This effect has been explored in detail by several authors using full-scale experiments [20–27], with scale models [28–30] and computational fluid dynamics CFD [23,31,32]. Many of these works replicate hospital isolation room scenarios. Despite abundant evidence that hinged doors induce greater air exchange through doorways compared to sliding doors, hinged doors are common in hospital isolation rooms, probably due to space restrictions. ORs, however, have more space and tend to have sliding doors.

It is difficult to obtain high quality spatial and temporal resolution quantitative experimental data on how door openings and HCW movement impact on the containment effectiveness of isolation cubicles. Some experimental studies only compare the influence of the type of door, whether hinged or sliding [32]. Another experimental study using scale models also takes into account foot traffic in addition to the type of door [33]. There are few experimental studies with the air-conditioning system in operation during door opening and/or passage of human traffic. Hang et al. [23] conduct full-scale experiments using tracer gas and CFD simulations to study potential airborne transmissions between two isolation rooms through a shared anteroom due to hinged door opening. They carried out experiments in which doors remained fully open for 30 and 300 s. The authors report that it is difficult to experimentally capture the evidence of inter-room airborne transmission if the door only remains open for 30 s. The tracer gas technique using photoacoustic spectroscopy has insufficient frequency response to study short transitory processes, such as door opening and closing cycles.

CFD is an increasingly common tool in ventilation flow analysis [34]. Stationary simulations are restricted to studying contaminant dispersion in an OR when the door is open, and contend that sliding door opening does not disturb flow [35,36]. In order to take door movements and foot traffic into account, transitory simulations must be performed. Certain studies that employ RANS (Reynolds-averaged Navier-Stokes equations) focus exclusively on gauging the impact of door opening and closing [21,37]. Choi and Edwards [38] used Large Eddy Simulation (LES) to examine contaminant transport through an open door due to realistic human walking motion under a variety of scenarios without ventilation. They conclude that contaminant entrainment in the wake induced by human motion is the dominant transport mechanism, although backward transport (opposite to the walking motion) can also occur due to downwash effects and tip vortex formation. They also noted that transport of contaminants in the direction of movement continues due to inertia even when the subject stops. In a subsequent study, the same authors [31] simulate a human walking from a contaminated room to a clean room through a vestibule and through two hinged or sliding doors. This simulation also includes ventilation with an exhaust in the vestibule and small gaps below the doors. The authors quantify the effects of door type and walking speed on contaminant transport although they point out that pressure effects are complex. Saarinen et al. [39] use LES to investigate the transient airflows generated during human passage through a hinged and sliding door between two rooms in an isothermal environment without ventilation. They compare the results with experimental measurements taken using real scale tracers. Shih et al. [40] use the RANS method to investigate the effects of a moving person and the opening and closing of a sliding door on room pressure and velocity distributions in an isolation room with anteroom. They indicate that the internal pressure within the isolation room rises suddenly the instant the door is opened and reaches the pressure of the anteroom one second after the door is opened. When the door is closing, the internal pressure drops quickly and becomes negative again. At the instant the door is completely closed, the internal room pressure is lower than the specified negative internal pressure and then rises rapidly to achieve the specified negative internal pressure. The only study found to date which explores these phenomena in an OR was published by Balocco et al. [41]. They use the RANS method to analyse the effects on OR climate, airflow patterns and indoor pressure, of a sliding door combined with people crossing through and people carrying a stretcher. The results obtained by these authors show disruptions of the airflow inside the OR and different airflow displacement and distribution caused by surgical staff movements and sliding door opening and closing, but, in particular, static pressure changes in the HVAC plant system with important effects on ventilation system working conditions.

As seen in the previous paragraph, CFD simulations are increasingly common to study transitory phenomena in indoor environments. In the case of door opening and closing and in the presence of ventilation systems, one of the main difficulties involved in CFD simulations lies in imposing realistic boundary conditions at air entry and exit points during the transitory process.

In this work, instantaneous airflows are measured during the passage of a person through a sliding door in a real OR with the HVAC system working under operating conditions. An ultrasonic anemometer that measures the magnitude and direction of the instantaneous air velocity in the doorway is used.

2. Experimental set-up

This study was performed in the main OR suite (surgical suite) at the University of Valladolid Hospital which contains 18 ORs organised in six blocks. Three of the blocks have four ORs and another three have two ORs. The OR studied forms part of a group of four ORs which share the access hall (Fig. 1). This hall also provides access to the dirty area as well as to the two staff preparation