Title

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

Authors

J.M. Villafruela [a]*, J.F. San José [a], F. Castro [a] and A. Zarzuelo [b]

[a]Department of Energy and Fluid Mechanics, University of Valladolid, 47011 Valladolid, Spain

[b]Hospital Clínico Universitario de Valladolid, 47005 Valladolid, Spain

*Corresponding Author

Tel: +34 983 184 408

Fax: +34 983 423 363

email: manolo@eii.uva.es

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.

Key words

operating room, door opening, sliding door, ultrasonic anemometry, foot traffic

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 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 rooms. Each staff preparation room serves two ORs.

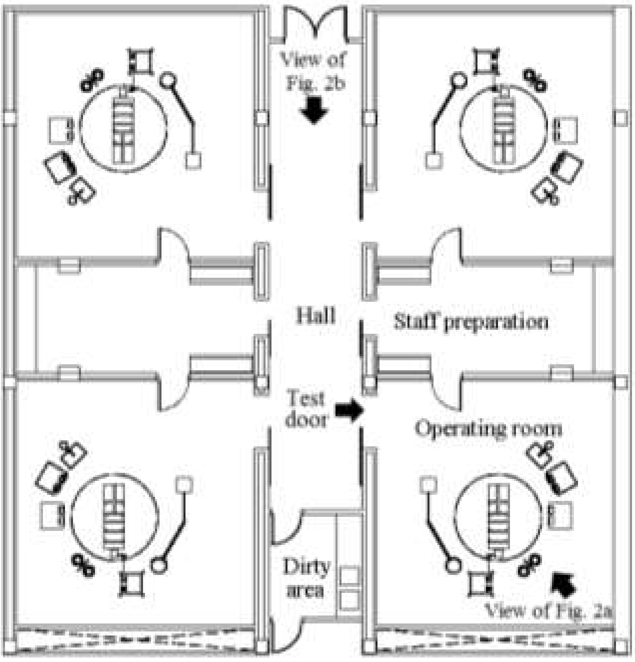


Fig. 1. OR block layout.

2.1. Air supply and extraction

Each OR has its own HVAC unit. Air supply into the areas shared by several ORs comes from another HVAC unit. The access hall to the OR has air supply and extraction. The OR and the hall have the same ambient temperature, 22ºC. Air supply and ambient air temperature may be considered practically the same. The supply and extraction ventilators in the OR are regulated so that in steady state and with the doors closed, the supply flow remains constant and in the OR an over-pressure of 20 Pa is achieved compared to the hall.

Air supply to the OR was through unidirectional vertical flow, also known as LAF ventilation (Fig. 2a). Through a rectangular surface measuring 1.76 × 1.74 m in the centre of the ceiling, 2700 m^3/h of air, equivalent to 18 air changes/hour, was introduced. Air extraction was performed through eight return air grilles located on the entry door wall and on the facing wall; four near ground level, measuring 38 × 10.5 cm^2 and four near the ceiling measuring 18 × 10.5 cm^2. The small differences detected between supply air and return air in the OR fall within the uncertainty range of the flow measuring equipment. Inspections were made of all the elements where air leakages might occur (doors, electrical fittings on the walls, control panel and information on ambient conditions, light fittings in the ceiling, etc.) to check whether they were perfectly sealed. All of this reflects the high degree of airtightness in the OR.


a) b)

Fig. 2. Pictures a) OR general view b) Hall general view.

2.2. Door opening

The door into the OR from the hall is a sliding door (Fig. 2b). The door slides on the outside of the OR. Seen from inside the OR, it opens right to left, in other words towards lower X values (Fig. 4). The door measures L=1.48 m and H=2.10 m.

In all experiments, the time from when the door starts to open until complete closure of the door is 14 s. The door takes 6 s to move from closed to fully open, remains wide open for 2 s and then takes 6 s to close from fully open to fully closed (Fig. 3). Door motion speed is 0.27 m/s. Hereinafter, the start of the door opening is taken as t = 0 s.

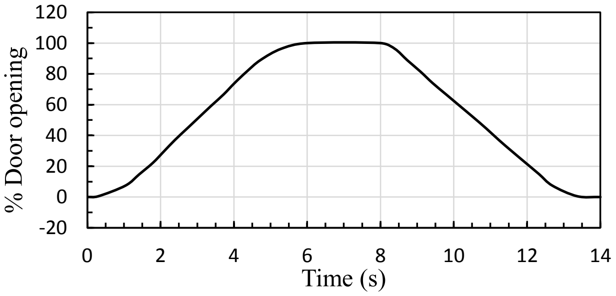


Fig. 3. Temporal variation of the door opening

2.3. Overpressure

The control system for OR air supply and extraction ventilators during the tests is as follows. With the doors closed and in steady state, the control system maintains 20 Pa ±1 Pa overpressure inside the OR compared to the hall. When the door opens, the control system detects the loss of differential pressure and gradually decreases the return airflow by half. Nevertheless, the supply air flow remains constant at 2700 m^3/h. Determining the system's response time proves difficult given the large number of parameters involved. However, by measuring the air velocity in the return air flow it was possible to estimate that the extraction flow stabilized between t=6 s and t=8 s, coinciding with the period when the door is wide open. When the door closes again fully, there is a sudden increase in OR pressure, above the initial 20 Pa, as a result of the difference between the air supply and return airflow in the OR. When it detects this increase in differential pressure, the system acts to re-establish the steady state conditions.

3. Tests

Air flow exchange between OR and hall through the communicating door is studied, with the other doors remaining closed at all times. In order to measure the air flow exchange, the instantaneous velocity field is calculated near the door which provides access to the OR from the hall during a full opening and closing cycle. Using an ultrasonic anemometer (type WA-590&TR-90T; Kaijo Sonic, Tokyo, Japan) simultaneous measurements are taken of the three velocity components over a range from 0 m/s to 10 m/s, with 2% uncertainty, 0.005 m/s resolution, and a sampling frequency of 10 Hz. The anemometer comprises three pairs of ultrasonic transmitter-receivers separated by 5 cm, such that the measuring volume is 5×5×5 cm^3.

In addition to measuring velocity, smoke visualisations were performed using theatre smoke. Flow visualisations were recorded with a digital camera (Canon 5D II, canon EF 24-70mm f/2.8 lens, full HD video, 1920x1080 px, 25 fps). The smoke machine was positioned outside in the hall. The camera was positioned in the OR, and a side view was recorded.

Three types of tests were carried out: a) door opening-closing, b) door opening, a person entering the OR and the door closing, and c) door opening and a person leaving the OR and door closing.

3.1. Test procedure

Velocity was measured at 24 points located on a plane parallel to the door and 10 cm inside the OR. Fig. 4 shows the measuring points, the nomenclature used and the reference system employed. For each point, the procedure for taking data was as follows: twenty seconds after the commencement of data recording on the anemometer and the differential pressure sensor, the order was given for the door to be opened. The door completes a full opening and closing cycle. The test concluded two minutes after commencing. The airflow in the OR was then allowed to stabilise for at least two minutes before the next test commenced.

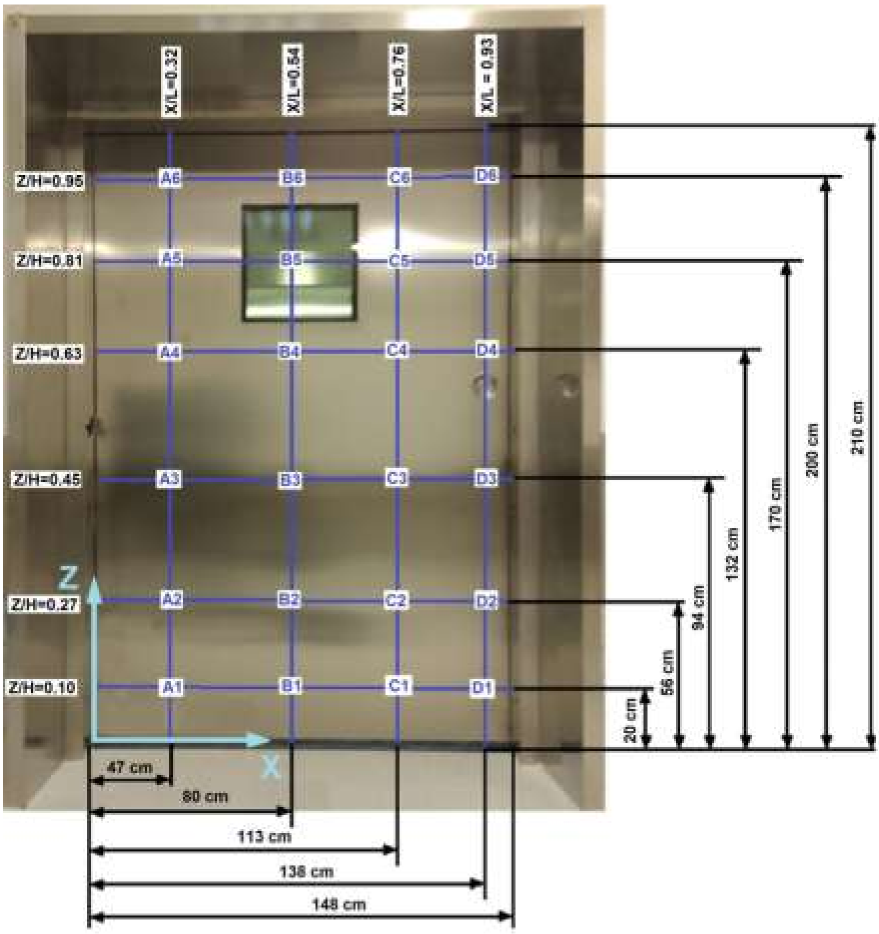


Fig. 4. Velocity measuring positions. Door seen from inside the OR.

3.2. Measurement repeatability

In order to evaluate the measurement repeatability, ten door-opening and closing tests were performed in various positions without human traffic. Fig. 5 shows the temporal mean of v_y in black trace together with the upper and lower variability limits in grey trace for position D4. Results are similar for the other velocity components and positions. Mean dispersion of the values compared to the mean (standard deviation) is below 0.025 m/s throughout the whole sampling period. For each measuring position and test it was decided to repeat the measurements twice and to average the values.

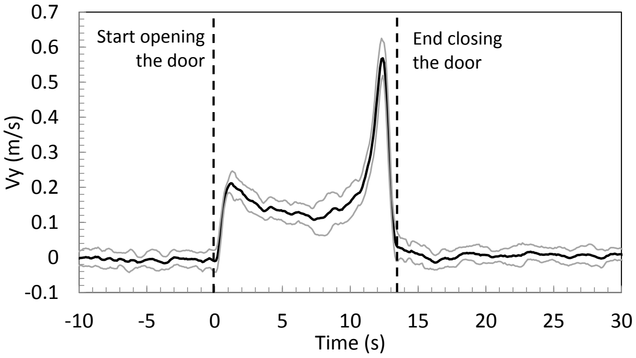


Fig. 5. Ensemble average of 10 tests in position D4 (Z/H=0.63, X/L=0.93)

4. Analysis of results

4.1. Opening and closing of the door

Fig. 6 shows the data given by the anemometer in position D6 during one opening and closing of the door without foot traffic. Up to t=0 s, the three velocity components are virtually negligible. Due to the position of point D6, as soon as the door is opened, the velocity field is altered. The v_y component is normal to the plane of the door. When v_y is greater than zero, air exits the OR towards the hall. This velocity component increases up to 0.2 m/s before gradually decreasing. When the door again approaches point D6 during the closing stage, there is a sudden increase in v_y up to 0.5 m/s before it then decreases again when door closure is complete. At this point, airflow is at all times outward from the OR to the hall. The v_x component, parallel to the door, behaves similar to v_y and the value of the vertical v_z component is close to zero throughout the whole process. This means that air movement in D6 may be considered horizontal.

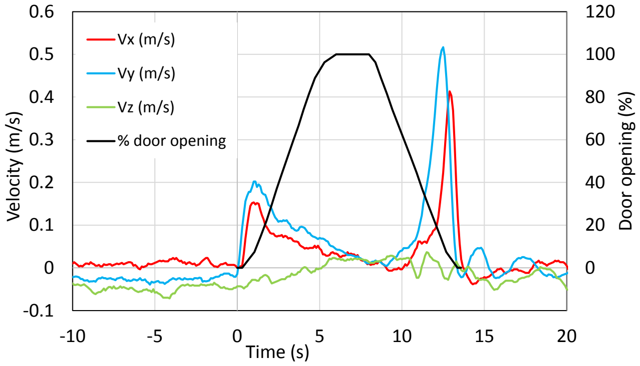
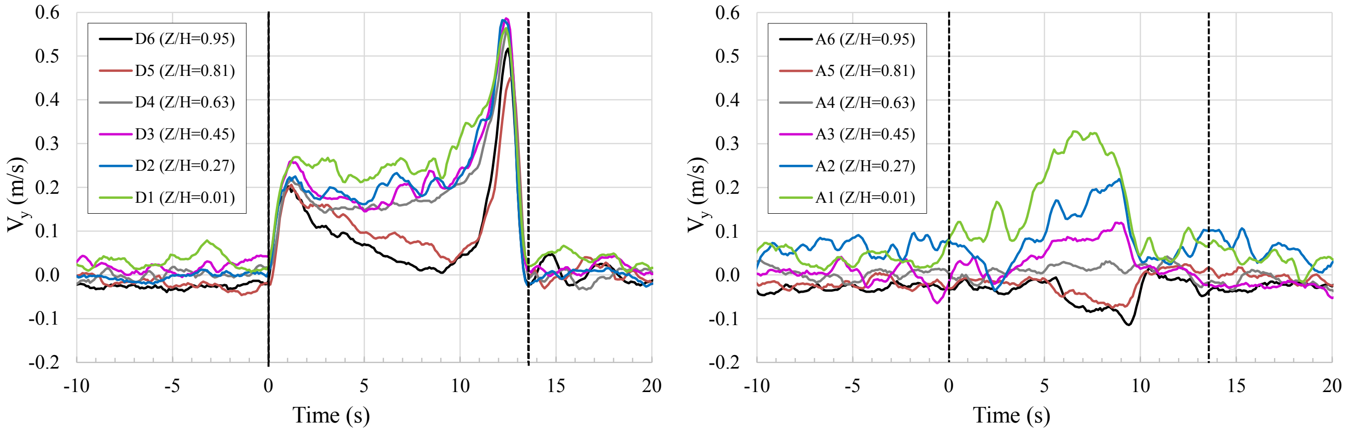


Fig. 6. Data provided by the anemometer. Test with no foot traffic. Position D6 (X/L=0.93, Z/H=0.95).

It should be noted that for t=0 s, the pressure difference is 20 Pa, such that as soon as the door opens there is an outflow of air because v_y increases. The pressure differential immediately disappears and the control system reduces the OR return outflow to 50% of its initial value. The door area increases and the total flow leaving through the door coincides with the difference between the airflow supplied and extracted by the OR ventilation system, such that velocity v_y diminishes. This difference in flows gradually increases until the exhaust fan again reaches steady state. When the door is closing, the exit area decreases and the velocity v_y tends to increase. As the difference between these airflows is at its highest, the maximum value of v_y is greater than when the door starts to open.

Fig. 7 shows how the temporal distribution of normal velocity v_y evolves over a vertical zone for the two extreme positions of X/L=0.93 and X/L=0.33. Clearly, as the door opens towards lower X values, the period during which the velocity is disturbed is lower for X/L=0.33 than for X/L=0.93. In both positions, it can be seen how the largest outgoing flows occur at the lower part of the door. At the upper part of the door, the outgoing flows tend to be lower or even to be incoming flows.



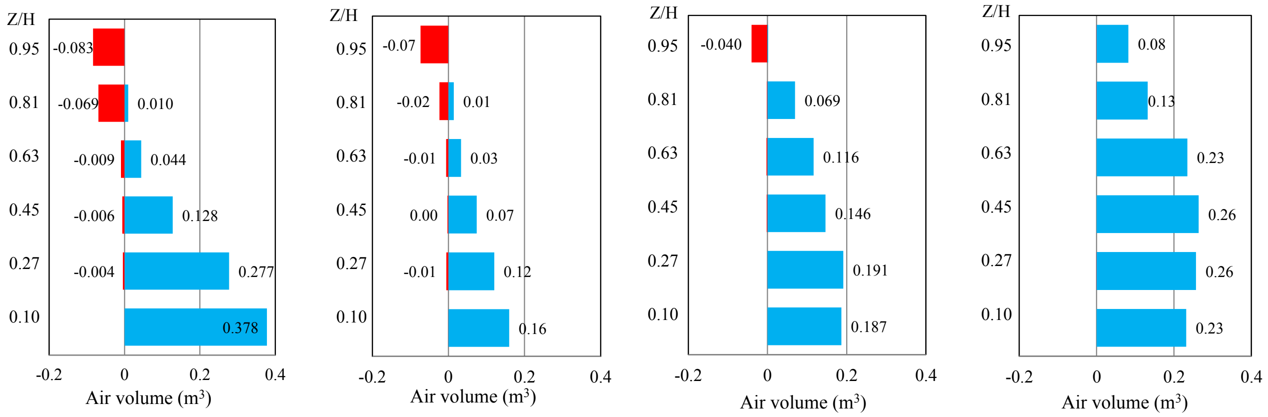
a) b)

Fig. 7. Temporal evolution of v_y with no foot traffic in the lines: a) X/L=0.93 b) X/L=0.32

Based on the velocity distributions, an estimation may be made of the instantaneous airflow that crosses the door. To do this, the geometric door space is discretised in regions linked to the measuring points such that when decomposed, each point is assigned to an area made up of the points which are closer to it than to any other point (Voronoi regions). Each region is assigned the velocity corresponding to the measuring point that defines it. The instantaneous airflow that crosses the door in each region is estimated by multiplying the velocity $v_y(t)$ by the area of each region. By integrating instantaneous flow from the moment the door opens until it finishes closing, the net volume of air that traverses the door in each region can be estimated. Adding up all the regions enables us to calculate the total volume of air that enters or leaves the OR. For example, velocity v_y of Fig. 6 is always positive such that the flow will always be outgoing at position D6 of the door. Integrating the velocity multiplied by the instantaneous area of region D6 gives an outgoing air volume of 90 litres.

Fig. 8 depicts the volume of incoming air (red) and outgoing air (blue) in the OR in each region during an opening-closing cycle of the door. Air entering the OR can be seen in the upper left part of the door (Video 1). At the rest of the door area, the air flows from the OR outwards towards the hall. Having both an incoming and outgoing airflow in a single area is due to the fact that during the time the door is opening and closing, the airflow direction may change.

Air mainly enters through the upper part of the door whereas most air leaves through the lower part, probably due to the flow pattern inside the OR generated by the vertical LAF ventilation. Temperature differences can cause this type of behaviour [42], although in this case the fluid field can be considered quasi-isothermal. In LAF ORs air flow tends to be horizontal near the floor and upward on the walls -before the door opens, v_z data is positive in all the door regions-. When the door opens, air tends to flow out the through the lower part of the doorway.



a) X/L=0.32 b) X/L=0.54 c) X/L=0.76 d) X/L=0.93

Fig. 8. Volume of air crossing the door in each region. In blue: air leaving the OR. In red: air entering the OR.

4.2. Opening and closing of the door with foot traffic

Having described the air velocity fields at the door of the OR during the opening-closing cycle, similar tests were carried out with a person entering and a person leaving during the opening and closing of the door. The person remains still at a distance of 0.25L from the door and begins to walk when the door reaches position X/L=0.32 (t=3.7 s) and then continues walking at a steady pace (a speed of 1 m/s) until they get as far away from the door as possible. Fig. 10 indicates the positions at the moment they start to walk. Measurements were only taken in two vertical zones, one each side of the area where the person walked (X/L=0.93 and X/L=0.54). For each measuring point, there were two opening-closing cycles with a person entering and a further two with the person exiting. The results shown are the average for the two cycles. In addition, in order to provide a better description of the fluid field, visualisations were conducted using smoke. In these, the hall was filled with smoke and the movement of the smoke towards the inside of the OR was recorded when the person was entering or exiting.

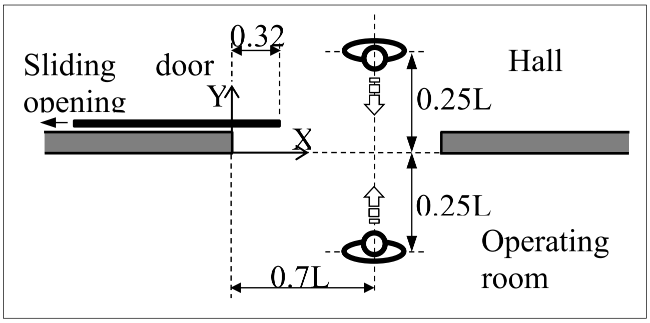
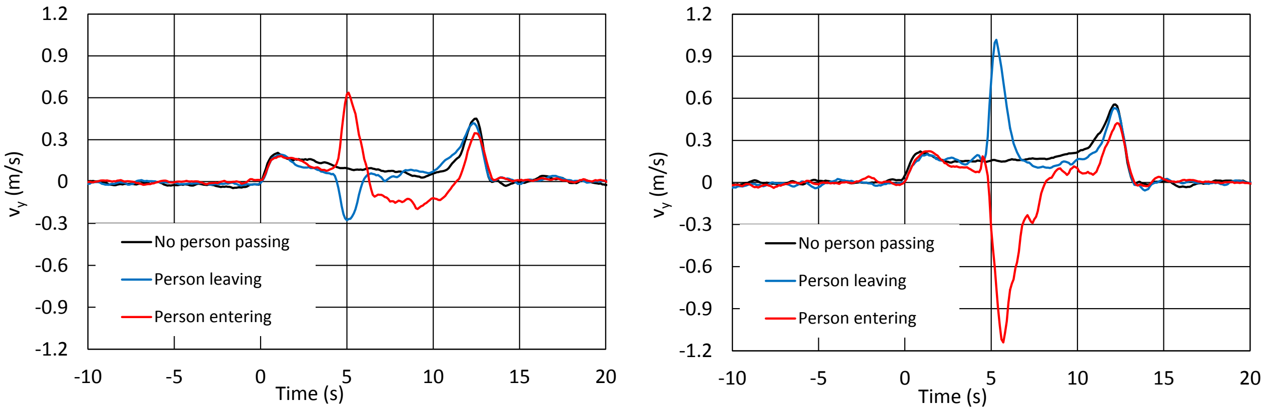


Fig. 9. Positions in which the person's movement commences.

In order to examine how a person passing through disturbs the velocity field, the results of the three types of test are shown together. First, an analysis is performed of what happens at positions X/L=0.93 corresponding to the vertical zone situated between the person and the right-hand part of the doorframe. Fig. 10a depicts the normal air velocity component v_y in position D5 (X/L=0.93, Z/H=0.81), in other words, at head height. When nobody is passing through, the airflow in this position is always outwards. When a person is entering, the velocity field remains the same as when there is nobody passing until the moment they cross through the door (t<4 s), at which point there is a sudden increase in v_y up to 0.6 m/s (t=5s) followed by a sharp drop to a negative value (6<t<11 s) with the subsequent entry of air. When the door is about to complete its closure (t>12 s), the velocity field is restored. Contrastingly, when someone is exiting, there is a sudden drop in v_y to -0.3m/s when they cross the door (t=5s), followed by an abrupt increase to positive values. For a few seconds (4<t<6 s) the air from the hall enters the OR.



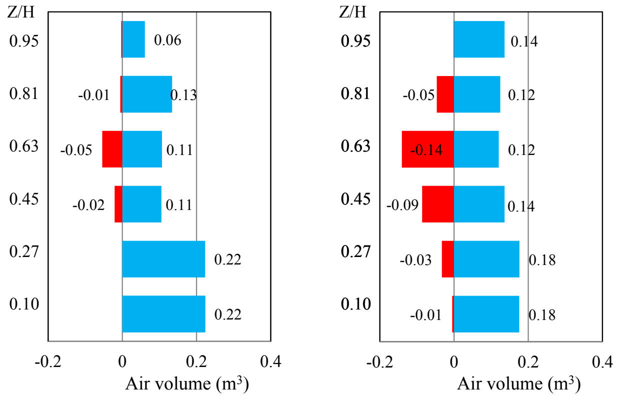
a)

b)

Fig. 10. Comparison between velocity v_y with and without a person passing in the positions in: a) D5 (X/L=0,93, Z/H=0,81) and b) D4 (X/L=0,93 Z/H=0,63).

At the person's chest height D4 (X/L=0.93, Z/H=0.63), the behaviour changes completely (Fig. 10b). When entering, v_y drops to -1.1 m/s, with the subsequent entry of air from the hall into the OR in the interval 4<t<8 s. However, when exiting, there is a sudden increase in velocity v_y to 1.0 m/s at t=4 s leading to an increase in the outgoing airflow that is leaving the OR. At the lower point D3 (Z/H=0.45), the behaviour is similar. At chest height, the maxima and minima in velocity are inverted and are more noticeable at head height, probably due to the fact that the gap between person and doorframe is smaller at chest height than at head height.

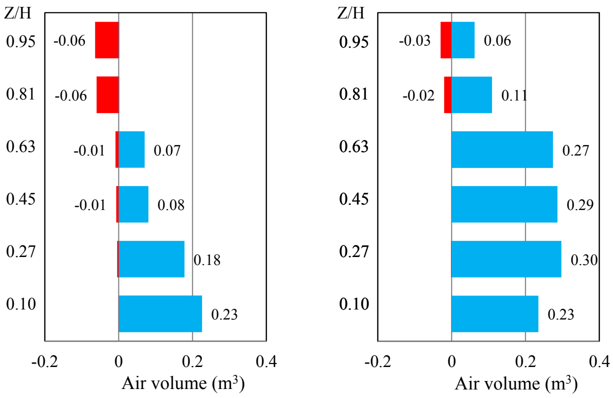
The volume of air that crosses the door in each region during the opening-closing cycle of the door and a person entering is shown in Fig. 11. Inflow of contaminated air from the hall occurs particularly in the gap between the person and the right-hand part of the doorframe, especially at chest height, where there is less gap. Visualisations with smoke sustain that the person's wake in the area of the chest drags air in with it, in this case, from the hall into the OR (Video 2). In the head region, this initially leads to a flow counter to the direction of movement. Subsequently, due to the effect of their wake, the person drags air inwards into the OR. These visualisations concur with those carried out by Kalliomaki et al. [43].



a) X/L=0.54 b) X/L=0.93

Fig. 11. Volume of air crossing the door in each region when a person enters. In blue: air exiting the OR. In red: air entering the OR.

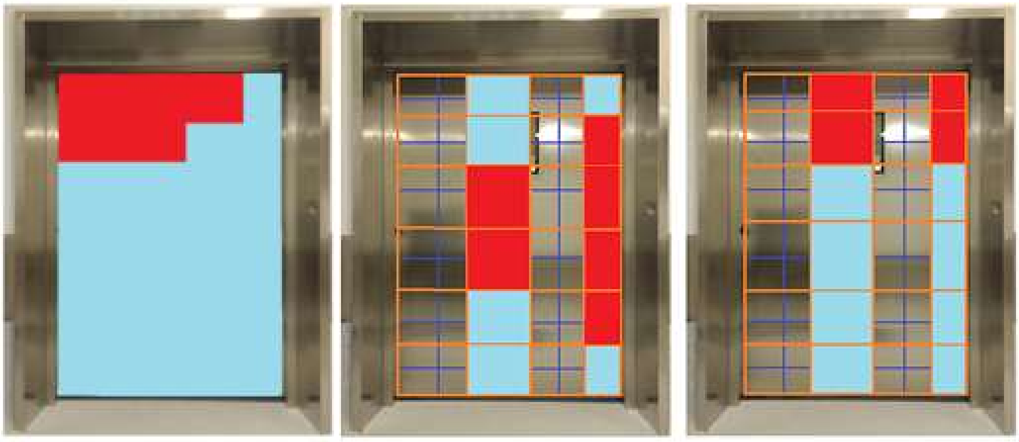
Fig. 12 shows the volume of air that crosses the door in each region during an opening-closing cycle and when a person is exiting (Video 3). The effect of the wake is the opposite of what happens when a person enters. When a person leaves the OR, air enters the through the same areas as when nobody is crossing the doorway.



a) X/L=0.54 b) X/L=0.93

Fig. 12. Volume of air that crosses the door in each region when a person leaves. In blue: air leaving the OR. In red: air entering the OR.

Comparing the direction of the airflows in the three cases reveals significant differences. Fig. 13 shows in red the areas where air enters the OR at some point when the door is opening, and in blue the areas where the airflow is always from the OR outwards towards the hall. This shows how foot traffic and the direction in which people walk can affect the temporal evolution of the flow pattern.



a) b) c)

Fig. 13. Zones where at some point the airflow is from the hall to the OR (in red) and where it is always from the OR to the hall (in blue). a) opening-closing b) opening-entry-closing. c) opening-exit-closing.

The volume of air entering and exiting the OR when a person comes through the door into the OR from the hall in all positions of X/L=0.54 and X/L=0.93 is shown in Table 1. When the person enters the OR, the entry of contaminated air from the hall is greater than when the person exits, and in both cases is greater than when there is only the opening and closing of the door.

Table 1. Estimation of the volume of air entering and leaving the OR in vertical zones X/L=0.54 and X/L=0.93

	Opening-closing	Opening-entry-closing	Opening-exiting-closing
Volume of air leaving the OR	1.60 m^3	1.72 m^3	1.82 m^3
Volume of air entering the OR	0.11 m^3	0.40 m^3	0.19 m^3

5. Conclusions

In the present work, original transient experimental measurements in a real OR with LAF ventilation are performed in order to assess the effect of sliding door opening/closing and foot traffic on the instantaneous air velocity field and air exchange through the doorway. The direction and velocity of the airflow were measured using a three-dimensional ultrasonic anemometer.

Before the door opens, the OR maintains a positive pressure difference of 20 Pa compared to the hall, which prevents air entering from adjoining enclosures. The opening of a sliding door causes sudden decreases in differential pressure and the containment effect is partially lost. In order to prevent air entering when the door opens, the airflow extracted from the OR is reduced. An outgoing net airflow equal to the difference between the supply and return airflow is generated through the door. However, despite all the preventive measures taken, it was found that even though outgoing air was dominant (3.14 m^3) there is also incoming air (0.33 m^3), even when there is nobody passing through the door. Air mainly enters through the upper part of the door whereas the lower part is through where most air leaves.

If, after the door opens, a person passes through, the airflow through the door changes. The direction the person takes was found to significantly influence the exchange volume. When a person enters, the volume of air entering the OR is greater on the side of the person closer to the doorframe, which would seem to indicate that moving away from the doorframe would minimise the amount of incoming air. A person exiting also causes air to come into the OR but to a lesser degree than when they enter.

Overall, despite the preventive measures adopted (air exchange rates, air tightness, positive pressure, sliding door, reduction of the exhaust airflow rate during door operation, ...) the coming and going of staff during an operation causes air to enter the OR from outside. Although there is a net outflow, some air will still be able to enter when the door opens and closes.

Acknowledgment

This research was supported by project DPI2014-55357-C2-1-R R from the Spanish National Government 2013-2016 R&D&I plan issued by the Ministry of Economy and Competiveness.

Bibliography

[1] M. Melhado, J.L.M. Hensen, M. Loomans, L. Forejt, Review of operating room ventilation standards, in: Proc. 17th Int. Air-Conditioning Vent. Conf. - STP - Soc. Environ. Eng.,

Prague, 2006.

[2] F. Castro, J.F. San José, J.M. Villafruela, A. Guijarro, Manual de diseño de la climatización y ventilación de quirófanos y habitaciones en centros hospitalarios de Castilla y León, Mata Digital, S.L., Valladolid (Spain), 2011.

[3] C.S. Hayden, G.S. Earnest, P.A. Jensen, Development of an Empirical Model to Aid in Designing Airborne Infection Isolation Rooms, J. Occup. Environ. Hyg. 4 (2007) 198–207.

[4] W.A.C.A.C. Zoon, M.G.M.G.M. van der Heijden, M.G.L.C.G.L.C. Loomans, J.L.M.L.M. Hensen, On the applicability of the laminar flow index when selecting surgical lighting, Build. Environ. 45 (2010) 1976–1983.

[5] F. Memarzadeh, A.P. Manning, Comparison of operating room ventilation systems in the protection of the surgical site, in: ASHRAE Trans., 2002: pp. 3–15.

[6] T.T. Chow, X.Y. Yang, Ventilation performance in the operating theatre against airborne infection: numerical study on an ultra-clean system, J. Hosp. Infect. 59 (2005) 138–147.

[7] J. Hang, Y. Li, R. Jin, The influence of human walking on the flow and airborne transmission in a six-bed isolation room: Tracer gas simulation, Build. Environ. 77 (2014) 119–134.

[8] H. Matsumoto, Y. Ohba, The Influence of a Moving Object on Air Distribution in Displacement Ventilated Rooms, J. Asian Archit. Build. Eng. 3 (2004) 71–75.

[9] S. Mazumdar, Y. Yin, A. Guity, P. Marmion, B. Gulick, Q. Chen, Impact of moving objects on contaminant concentration distributions in an inpatient ward with displacement ventilation, HVAC R Res. 16 (2010) 545–563.

[10] J. Wang, T.-T. Chow, Numerical investigation of influence of human walking on dispersion and deposition of expiratory droplets in airborne infection isolation room, Build. Environ. 46 (2011) 1993–2002.

[11] Y. Wu, N. Gao, The dynamics of the body motion induced wake flow and its effects on the contaminant dispersion, Build. Environ. 82 (2014) 63–74.

[12] H. Brohus, K.D. Balling, D. Jeppesen, Influence of movements on contaminant transport in an operating room., Indoor Air. 16 (2006) 356–372. doi:10.1111/j.1600-0668.2006.00454.x.

[13] T.-T. Chow, J. Wang, Dynamic simulation on impact of surgeon bending movement on

bacteria-carrying particles distribution in operating theatre, Build. Environ. 57 (2012) 68–80.

[14] R.J. Lynch, M.J. Englesbe, L. Sturm, A. Bitar, K. Budhiraj, S. Kolla, Y. Polyachenko, M.G. Duck, D.A. Campbell, Measurement of foot traffic in the operating room: implications for infection control., Am. J. Med. Qual. 24 (2009) 45–52.

[15] Y. Babkin, D. Raveh, M. Lifschitz, M. Itzchaki, Y. Wiener-Well, P. Kopuit, Z. Jerassy, A.M. Yinnon, Incidence and risk factors for surgical infection after total knee replacement, Scand. J. Infect. Dis. 39 (2007) 890–895.

[16] S. Scaltriti, S. Cencetti, S. Rovesti, I. Marchesi, A. Bargellini, P. Borella, Risk factors for particulate and microbial contamination of air in operating theatres., J. Hosp. Infect. 66 (2007) 320–6.

[17] A.E. Andersson, I. Bergh, J. Karlsson, B.I. Eriksson, K. Nilsson, Traffic flow in the operating room: an explorative and descriptive study on air quality during orthopedic trauma implant surgery., Am. J. Infect. Control. 40 (2012) 750–5.

[18] E.B. Smith, I.J. Raphael, M.G. Maltenfort, S. Honsawek, K. Dolan, E.A. Younkins, The effect of laminar air flow and door openings on operating room contamination., J. Arthroplasty. 28 (2013) 1482–5.

[19] P. Panahi, M. Stroh, D.S. Casper, J. Parvizi, M.S. Austin, Operating Room Traffic is a Major Concern During Total Joint Arthroplasty, Clin. Orthop. Relat. Res. 470 (2012) 2690–2694.

[20] L. Chang, X. Zhang, Y. Cai, Experimental determination of air inleakage to pressurized main control room caused by personnel entering, Build. Environ. 99 (2016) 142–148.

[21] L. Chang, X. Zhang, S. Wang, J. Gao, Control room contaminant inleakage produced by door opening and closing: Dynamic simulation and experiments, Build. Environ. 98 (2016) 11–20.

[22] P. Kalliomäki, P. Saarinen, J.W. Tang, H. Koskela, Airflow patterns through single hinged and sliding doors in hospital isolation rooms, Int. J. Vent. 14 (2015) 111–126.

[23] J. Hang, Y. Li, W.H.H. Ching, J. Wei, R. Jin, L. Liu, X. Xie, Potential airborne transmission between two isolation cubicles through a shared anteroom, Build. Environ. 89 (2015) 264–278.

[24] Gustavsson N., Dispersion of small particles into operating rooms due to openings, Chalmers University Of Technology, Göteborg, Sweden, 2010.

[25] T. Zhang, K. Lee, Q. Chen, A simplified approach to describe complex diffusers in displacement ventilation for CFD simulations, Indoor Air. 19 (2009) 255–267.

[26] D.E. Kiel, D.J. Wilson, Combining door swing pumping with density driven flow, ASHRAE Trans. 95 (1989) 590–599.

[27] J. Hendiger, M. Chludzińska, P. Ziętek, Influence of the Pressure Difference and Door Swing on Heavy Contaminants Migration between Rooms., PLoS One. 11 (2016) e0155159.

[28] L. Fontana, A. Quintino, Experimental analysis of the transport of airborne contaminants between adjacent rooms at different pressure due to the door opening, Build. Environ. 81 (2014) 81–91.

[29] J.W. Tang, I. Eames, Y. Li, Y.A. Taha, P. Wilson, G. Bellingan, K.N. Ward, J. Breuer, Door-opening motion can potentially lead to a transient breakdown in negative-pressure isolation conditions: the importance of vorticity and buoyancy airflows., J. Hosp. Infect. 61 (2005) 283–6.

[30] E. Sansone, S. Keimig, The influence of door swing and door velocity on the effectiveness of directional airflow, in: Proc. ASHRAE IAQ '87, 1987: pp. 372–381.

[31] J.-I. Choi, J.R. Edwards, Large-eddy simulation of human-induced contaminant transport in room compartments., Indoor Air. 22 (2012) 77–87.

[32] S. Lee, B. Park, T. Kurabuchi, Numerical evaluation of influence of door opening on interzonal air exchange, Build. Environ. 102 (2016) 230–242.

[33] J.W. Tang, A. Nicolle, J. Pantelic, C.A. Klettner, R. Su, P. Kalliomaki, P. Saarinen, H. Koskela, K. Reijula, P. Mustakallio, D.K.W. Cheong, C. Sekhar, K.W. Tham, Different types of door-opening motions as contributing factors to containment failures in hospital isolation rooms., PLoS One. 8 (2013) e66663.

[34] P. V Nielsen, Fifty years of CFD for room air distribution, Build. Environ. 91 (2015) 78–90.

[35] S. Dong, G. Tu, R. Cao, Z. Yu, Numerical study on effects of door-opening on airflow patterns and dynamic cross-contamination in an ISO class 5 operating room, Trans. Tianjin

Univ. 15 (2009) 210–215.

[36] C. Balocco, G. Petrone, G. Cammarata, P. Vitali, R. Albertini, C. Pasquarella, Indoor Air Quality in a Real Operating Theatre under Effective Use Conditions, J. Biomed. Sci. Eng. 7 (2014) 866–883.

[37] E.S. Mousavi, K.R. Grosskopf, Airflow patterns due to door motion and pressurization in hospital isolation rooms, Sci. Technol. Built Environ. 22 (2016) 379–384.

[38] J.-I. Choi, J.R. Edwards, Large eddy simulation and zonal modeling of human-induced contaminant transport., Indoor Air. 18 (2008) 233–49.

[39] P.E. Saarinen, P. Kalliomäki, J.W. Tang, H. Koskela, Large Eddy Simulation of Air Escape through a Hospital Isolation Room Single Hinged Doorway—Validation by Using Tracer Gases and Simulated Smoke Videos, PLoS One. 10 (2015) e0130667.

[40] Y.-C. Shih, C.-C. Chiu, O. Wang, Dynamic airflow simulation within an isolation room, Build. Environ. 42 (2007) 3194–3209.

[41] C. Balocco, G. Petrone, G. Cammarata, Assessing the effects of sliding doors on an operating theatre climate, Build. Simul. 5 (2012) 73–83.

[42] D.J. Wilson, D.E. Kiel, Gravity driven counterflow through an open door in a sealed room, Build. Environ. 25 (1990) 379–388.

[43] P. Kalliomäki, P. Saarinen, J.W. Tang, H. Koskela, Airflow patterns through single hinged and sliding doors in hospital isolation rooms – Effect of ventilation, flow differential and passage, Build. Environ. (2016).