AIRFLOW PATTERNS THROUGH A SINGLE HINGED AND A SLIDING-DOOR IN HOSPITAL ISOLATION ROOM

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Keywords: Isolation room, Airflow, Doorway, Tracer gas, Smoke visualization

SUMMARY

Airflow patterns through a single-hinged and sliding-door, in combination with human passage (simulated with a moving mannequin), inside a full-scale hospital isolation room mock-up, were compared. Experiments were conducted in still air (i.e. without ventilation). Tracer gases were used to quantify the airflow movement between the rooms caused by door-opening actions. Door-opening angle, total cycle time, door-hold open time, opening and closing speeds, and walking speed were varied to investigate their effects. Smoke visualisation of airflow patterns through the doorways were performed for selected cases. Average ranges of airflow volumes through the hinged- and sliding-doors were 1.3–2.5 m³ and 0.3–1.1 m³, depending on the parameter values, respectively. Relative to the hinged-door, less air flowed through the sliding-door, as induced by the door-opening motion. Hence, although the mannequin passage increased the air exchange across the doorway, its effects were much greater, relatively, for the sliding- than for the hinged-door.

INTRODUCTION

Pandemic outbreaks of airborne infectious diseases such as SARS and influenza A/H1N1 increased the need and usage of hospital isolation rooms significantly. In hospitals, patients with such highly contagious diseases are usually placed in a negative pressure isolation room to prevent further spreading of the disease, to protect patients, staff and visitors. However, containment failures happen and the operation of the isolation room doors may well be one of the main contributors (Tang et al., 2006). A case study by Tang et al. (2005) showed that at least in one case the operation of isolation room doors has resulted in a containment failure.

A review of experimental studies by Hyttinen et al (2011) demonstrated that the performance of the isolation rooms has been under intense examination. However, there are fewer studies about the effect of door-opening motion on air exchange between the isolation room and anteroom/corridor. Hayden et al (1998) used tracer gas in an isolation room mock-up and showed that the door-opening and mannequin passage through the doorway caused significant amounts of air to migrate through the doorway. Rydock and Eian (2004) used tracer gas in a real hospital environment and studied the tracer migration with a technician exiting an isolation room. They found elevated tracer gas values in the anteroom and also in the corridor. Adams et al (2011) studied the effect of pressure differential on containment effectiveness. They used fluorescent particles in a real hospital isolation room and measured particle
concentrations in anteroom and corridor when a care provider exited the isolation room through the anteroom into the corridor. They also found that human passage reduced containment and concluded that it was improved with increasing the pressure differentials between the rooms to counteract and reduce these uncontained airflows across the doorways.

More recently, this team has published qualitative findings on both single and double, hinged- and sliding-door scenarios, with and without simulated human passage, using a small-scale (1:10 scale compared to these current full-scale experiments) water-tank model with food-dye visualization (Tang et al., 2013). These experiments demonstrated that the hinged-door design generates the greatest amount of air exchange across the isolation room doorway, as compared to the sliding-doors. The human passage motion through the doorway contributes some additional air exchange across the doorway, however, this is relatively less for the hinged-door than the sliding-door scenario, as the air movement induced by the sliding-doors is much less than that induced by the hinged-doors.

This study is a part of an international project measuring, visualizing and modelling the airflow patterns across the isolation room doorways. In the project the partner institutions, the Finnish Institute of Occupational Health (FIOH), Finland, and National University Hospital (NUH), Singapore, studied the airflow patterns using full-scale air (FIOH) and small-scale water models (NUH), with latter having already published their findings (Tang et al., 2013).

**METHODOLOGIES**

**A Full-scale Isolation Room Model**

The model consisted of two identical rooms separated by a wall with a door in the middle. The rooms were 4.70 m wide, 4.00 m long and 3.00 m high. Inside the model, there was a 5.00 m long motorized rail running on the floor between the rooms, equipped with a small cart carrying 1.73 m high mannequin made out of foamed plastic. In this study we used two different door types, i.e. hinged and sliding-doors. In both cases, the doorway was 2.06 m high and 1.13 m wide. Doors were operated by an automated door operator. There were four thermometers inside the isolation room model, two in each of the rooms, for monitoring the temperature and temperature stratification. In this paper all the measurements and visualizations were carried out in still-air (i.e. without any ventilation).

**Tracer Gas Measurements**

Tracer gas measurements were used to quantify the airflow through the doorway with and without simulated passage for both hinged and sliding-door cases. Two tracer gases, sulfur hexafluoride (SF$_6$) and nitrous oxide (N$_2$O) allowed the airflow volume to be determined in both directions across the doorway. The two rooms on either side of the doorway were filled with each of the tracer gases (i.e. only one of the gases in each room), prior to the experiment. Fans in both rooms ensured proper mixing, but were shut down for the time the door was under operation. A gas analyzer collected samples through two perforated tubes, one in each room. Background concentrations outside the rooms were also monitored. Samples were collected from these three locations, serially, at 1 minute intervals. The analysis of the tracer gas measurements was based on the conservation of the gases:

$$
\begin{align*}
\Delta \sigma_i V_i &= \sigma_i X_i - \sigma_i X_i \\
\Delta \sigma_A V_A &= \sigma_i X_i - \sigma_A X_A,
\end{align*}
$$

(1)
where \( X_I, V_I, \tau_I, \Delta \tau_I, \sigma_I, \Delta \sigma_I \) are airflow (m\(^3\)) out of the isolation room, isolation room volume (m\(^3\)), isolation room SF\(_6\) concentration prior door opening (ppm), SF\(_6\) concentration change in the isolation room (prior and after the door operation), isolation room N\(_2\)O concentration prior to door opening (ppm) and N\(_2\)O concentration change in isolation room (prior and after the door operation) correspondingly. Equivalent parameters for the anteroom are marked with subscript \( A \). Solving for \( X_I \) and \( X_A \) we get:

\[
\begin{align*}
X_A &= \frac{\tau_I \Delta \sigma_I V_I + \sigma_I \Delta \tau_I V_A}{\sigma_A \tau_I - \sigma_I \tau_A} \\
X_I &= \frac{\tau_I \Delta \sigma_I V_I + \sigma_I \Delta \tau_I V_A}{\sigma_A \tau_I - \sigma_I \tau_A}
\end{align*}
\]  

(2)

Each experiment consisted of 5-7 door openings (with 45 minutes separation) after which the tracer gases were flushed away from the rooms before a new measurement with different door parameter values started. After the measurements for the hinged-door were completed, the sliding-door was installed and corresponding measurements completed with it.

**Smoke Visualizations**

Smoke visualizations were done to qualitatively illustrate the comparative airflow patterns between the hinged- and sliding-door designs. After the smoke was injected in one of the rooms and let to mix in properly, a narrow horizontal or vertical sheet of the doorway, in the empty room, was illuminated with theater spotlights. The flow visualization was recorded with a digital camera from four different angles in separate, consecutive experiments (or ‘takes’, as only one camera was available) with identical experimental parameters. The views included two side and two top-views (from isolation and anteroom side). A vertical light-sheet was used to illuminate the side-views for recording and a horizontal light-sheet was used when recording the top-views.

**RESULTS AND DISCUSSION**

**Smoke Visualizations**

Figures 1 (A)-(D) and 2 (A)-(D) show a series of still images obtained from the smoke videos for the hinged-door. Figures 3 and 4 show the same set of still images for the sliding-door. In these figures (A) depicts the situation before the door is opened, (B) after the door has opened, (C) during the mannequin passage and (D) the final situation after the mannequin has stopped and the door has closed again.

Qualitative visual examination of the figures indicates that the hinged-door creates a pronounced flow through the doorway and the smoke spreads further inside the anteroom than with the sliding-door. For the hinged-door the effect of mannequin passage is difficult to determine (Fig. 1 (C) and 2 (C)). The drastic influence of the door itself overshadows the impact of the passage. However, after the mannequin has stopped and the door closed (Fig. 1 (D) and 2 (D)), the air dragged by the mannequin fills the front part of the room thus indicating significant amount of air moved by the mannequin. For the sliding-door the influence of the passage is much more distinct and one can even notice the trailing wake of the mannequin (Fig. 3 (C) and 4 (C)).
Figure 1. Smoke visualization of the hinged-door and the mannequin passage showing the resulting airflow patterns (anteroom side view).

Figure 2. Smoke visualization of the hinged-door and the mannequin passage showing the resulting airflow patterns (anteroom top view).
Figure 3. Smoke visualization of the sliding-door and the mannequin passage showing the resulting airflow patterns (anteroom side view).

Figure 1. Smoke visualization of the sliding-door and the mannequin passage showing the resulting airflow patterns (anteroom top view).
Tracer gas measurements

Figure 5 (A) depicts the airflow to both directions caused by the action of the hinged- and sliding-door types. In this case the door opening took 3 s, it was held open for 8 s and closed in 5 s. The sliding-door caused a 0.55 m$^3$ airflow volume (average over both directions) through the doorway and hinged-door 1.34 m$^3$, correspondingly. Less airflow with sliding-door was expected based on the qualitative smoke visualizations. An approximately equal amount of air migrating to both directions was measured with both the door types. Hence, in future only the results from isolation room to anteroom will be shown. These results are consistent with Hayden et al (1998), who also found significant differences between hinged and sliding-door (although using ventilation and pressure difference in their study).

Figure 5 (B) shows the difference between a half-open (45° or 0.55 m) and fully-opened (90° or 1.13 m) doorway for the hinged- and sliding-doors. The airflow volumes for half- (and fully-opened) sliding and hinged-doors were on average 0.31 m$^3$ (0.56 m$^3$) and 1.16 m$^3$ (1.39 m$^3$) correspondingly. Eames et al (2009) studied the effect of opening angle in a small-scale water model. They also concluded that reducing the angle from 90° caused the amount of flow to decrease notably.

Figure 5 (C) shows the effect of total cycle time (mixture of various opening, on hold and closing durations) on the airflow across the doorway. With the shortest (longest) total cycle time the migrating volumes were on average 1.37 m$^3$ (2.42 m$^3$) and 0.29 m$^3$ (1.11 m$^3$) for the hinged and the sliding-door, correspondingly. Thus, with both door types the amount of air migrating through the doorway increases with total cycle time. In addition, the airflow volume across the doorway caused by the sliding-door action is significantly less than that with the hinged-door.

Figure 5 (D) depicts the effect of door hold-open (90° opening) time on the airflow through the doorway for the hinged- and sliding-doors. In this case the opening and closing duration were kept constant, 3 s and about 5 s respectively. One can see that the increasing hold-open time raises the amount of migrating air. This increase seems to correlate well with the increase found with total cycle time. Again there is considerable difference between hinged and sliding-door results, sliding-door action creating much less air exchange between rooms.

The effect of opening and closing duration (speed) on the amount of airflow is presented in Figure 5 (E). In this experiment the hold open time was kept constant (8 s). With fastest (slowest) door motion the averaged airflow volumes were 1.39 m$^3$ (1.81 m$^3$) and 0.56 m$^3$ (0.92 m$^3$) for the hinged and the sliding-door, respectively. The faster the door moves the smaller the amount of air migrating across the doorway. In contrast, Kiel and Wilson (1989) showed, in full-scale and small-scale models, that the volume through the doorway increased with increasing swing door speed, whereas Hayden et al (1998) found no significant effect of swing door speed to the amount of airflow across the doorway. This case needs further analysis and experiments with ventilation and pressure difference. As in previous cases, the airflow volume caused by the sliding-door is substantially less than with hinged-door.

Figure 5 (F) shows the combined effect of the door opening motion and the mannequin passage on the amount of airflow. The door opening, hold and closing times were kept constant (3 s, 8 s and 5 s respectively). Without passage (0 m/s, door operation only) the airflow was on average 0.56 m$^3$ and 1.39 m$^3$ for sliding- and hinged-doors. With 1 m/s (2 m/s) walking speed the airflow volumes were 1.65 m$^3$ (1.92 m$^3$) and 0.92 m$^3$ (0.89 m$^3$) for hinged- and sliding-doors respectively. The effect of increasing the passage speed is unclear; with the
hinged-door it increases the airflow, whereas with sliding-door it does not seem to affect the situation. Hayden et al (1998) also concluded that mannequin passage increased the airflow volume notably especially with a sliding-door. However, they did not find any significant difference between hinged and sliding-doors when combined with a mannequin passage.

Figure 5. The effect of different door parameters on the migrated air volume, as given by tracer gas measurements.
CONCLUSIONS

Smoke visualizations demonstrate that the opening motion of the sliding-door creates less airflow through the doorway. The effect of passage is significant with both door types yet more distinct with sliding-door. Half-open door decreases the amount of air migrating across the doorway substantially. The longer the total cycle and hold-open times the greater the airflow through the doorway. The faster the door motion the smaller is the amount of air migrating across the doorway. The detected effect of the door speed is against the results of previous studies and needs to be further studied. Passage increases the airflow between the rooms significantly (especially with the sliding-door) whereas the effect of passage speed is unclear. Overall, substantially less air is seen and measured to flow out of the isolation room with the sliding-door setup. In the future, the performance of the hinged- and sliding-doors will be compared under the influence of ventilation and pressure difference.

ACKNOWLEDGEMENT

Funding for this study was provided by the Finnish Funding Agency for Technology and Innovation (TEKES). It was part of a project co-funded by TEKES and A*STAR (Agency for Science, Technology and Research).

REFERENCES