Designing Simplified Airborne Infection Isolation Rooms to Reduce Infection Rate in Future Pandemics

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ABSTRACT

International travelling is growing rapidly, increasing the risk of spreading airborne infectious diseases such as influenza or SARS. In case of pandemic outbreaks, the demand for airborne infection isolation rooms (AIIRs) can be urgent. The challenge today is that there is only a limited number of AIIRs in each hospital. The rooms are expensive to build and airflow control to avoid contamination is often complicated.

Computational Fluid Dynamics (CFD) simulations have been performed to study the air flow patterns in an AIIR. The results are compared with laboratory experiments in a full-scale test chamber. The results from the baseline cases, consisting of a typical single bed patient room with balanced ventilation, showed that door opening and exiting the patient room can lead to an air transfer of up to 781 L (27.6 ft3) of potentially contaminated air. This means that high air exchange rates and long waiting time are necessary to dilute the air in the anteroom before the health care worker can exit the AIIR.

Instead of high air exchange rates and emphasis on the dilution of air, this paper proposes a design for simplified AIIRs that focuses on air flow patterns and air movement. Results from CFD simulations and laboratory experiments of the simplified solution show that installing a ventilation unit that supplies a high air volume into the anteroom through low velocity corner diffusers, significantly reduces the air escaping the patient room during door operation. 300 L/s (10.6 ft3/s) of diffuse air reduced the air transfer due to door opening and passage by 72-75 %. 500 L/s (10.6 ft3/s) diffuse air flow resulted in an 80-86% reduction, while 1000 L/s (35.3 ft3) gave an 85-96% reduction compared to the baseline cases. The results show that the ventilation unit can significantly reduce the amount of contaminated air that escapes the patient room. This will enable hospitals and other healthcare facilities to be better prepared for future pandemics, and also meet the current challenges to limit the spread of airborne diseases.

INTRODUCTION

In the last decades there has been a major international concern about Severe Acute Respiratory Syndrome (SARS) and avian influenza in humans. This has raised new scientific challenges, caused major human suffering and imposed enormous economic damage (WHO, 2007). The trends with increasing risk of airborne infections are probably driven by growth in the human population, urbanization, changes in the interactions between human and animal populations, climate change, and increases in international travel and trade (Khan et al. 2013). In case of pandemic outbreaks, the demand for airborne infection isolation rooms (AIIRs) can be urgent. The Norwegian National Influenza Pandemic

Preparedness Plan (2014) states that Norway (population: 5,5 mill) must be able to face a possible pandemic with an attack rate of 25%. This means that hospitals must be able to take up to 14-16.500 admissions (0.025-0.03% of the population in Norway). The contingency plans for all four health regions in Norway point out that there is a lack of isolation rooms, and some of the healthcare regions are completely missing AIIRs. The reason for this is most likely that the rooms are too expensive to build and to operate, and that airflow control to avoid contamination is complicated. This paper proposes a method for how to change a normal patient room into a simplified AIIR. Before considering solutions, there is a need to identify the main causes to contamination risk both in normal patient rooms and in AIIRs.

A normal AIIR is in negative pressure related to the adjacent zones to ensure that contaminated air does not escape to the surroundings. The Norwegian Isolation Guidelines recommend that the pressure differential between the rooms should be no less than 15 Pascals and that the air change rate should be at least 12 ACH (Isoleringsveilederen, 2004). However, according to Hyttinen (2011) the scientific evidence for the pressure differential limit values are insufficient. Complete containment seems to be impossible in spite of the use of very high pressure differentials and air exchange rates. Even if the ventilation rate exceeds 12 ACH, the waiting time in an anteroom that is necessary to dilute the air will be about 1 hour, which is unrealistically long (Hyttinen et al., 2011). In an ideal case with mixing factor of 1 it would take about 23 mins to reduce the concentration by 99 %. However, Hyttinen is referring to Mead et al. (2008) which are assuming mixing factor of 3, resulting in about 1 hour to reduce the concentration by 99%. Also, opening the door causes the pressure differential to cease, allowing airborne contaminants to freely escape to the adjacent spaces. It has been estimated through previous research that door opening and passage through the doorway is among the main factors causing containment failures in an AIIR (Hayden et al. (1998), Saarinen et al (2015) and Kalliomäki et al. (2016)). It is assumed that this is also the case for normal patient rooms without any pressure differential between the rooms.

As a part of this research study, the air volume transfer due to door opening and passage has been investigated. The results are presented in previous publications and are hereby referred to as the "baseline cases". The baseline cases consisted of opening a hinged door connecting an anteroom and a patient room with balanced ventilation and isothermal conditions, i.e. no temperature difference between the two rooms. Three cases were tested with both CFD simulations and laboratory experiments: (1) door opening without passage, (2) entering the patient room from the anteroom and (3) exiting the patient room to the anteroom. The results are well in line with the previous research. Between 730 to 800 liters (25.8 to 28.3 ft³) of air was transferred from the patient room, depending on if the person was exiting or entering the patient room. The results from the CFD simulations generally agreed with the results from the laboratory experiments, but they also revealed that both the velocity of the person and the actual moving pattern of the person seem to influence the air volume transfer (Harsem et al., 2018).

METHODS

The idea of designing simplified AIIRs is to install a single ventilation unit into a normal patient room. The ventilation unit is installed as an addition to the existing ventilation, i.e. the existing ventilation for person and material emissions runs as normal and is not altered. The installed ventilation unit will only operate when the door is open for a few seconds and is not expected to affect the room temperatures. It is assumed that the cooling demand and other requirements are considered when the patient room was designed. To enable a comparison of the results to the baseline cases ("normal patient room"), the idea has been tested using the same layout and geometries, ventilation rates, heat sources and temperature levels as presented in previous publications (Harsem et al., 2018). The volume of the patient room was 48,9 m³ (1727 ft³) and the anteroom volume was 14.1 m³ (498 ft³). The background ventilation rates were the same as in the baseline cases, yielding an air exchange rate of close to 4 ACH in both rooms. The inlet temperature was 18.5 °C (65.3 °F). The room temperature was 22.5 °C (72.5 °F) in both rooms. The door area was 2.5 m² (27.1 ft²) and it had a 2 cm (0.8 in) gap below. The door opened 45 degrees towards the patient room.

Since door opening, and passage, seem to be among the major factors causing containment failures, this paper focuses on testing if the ventilation unit can reduce, or at best eliminate, this risk. The basic idea is to install a ventilation

supply unit that recirculates a large air volume from the patient room and supplies it back towards the anteroom trough corner diffusers. The ventilation unit consists of a VAV fan, ducts, filters and corner diffusers as shown in Figure 1.
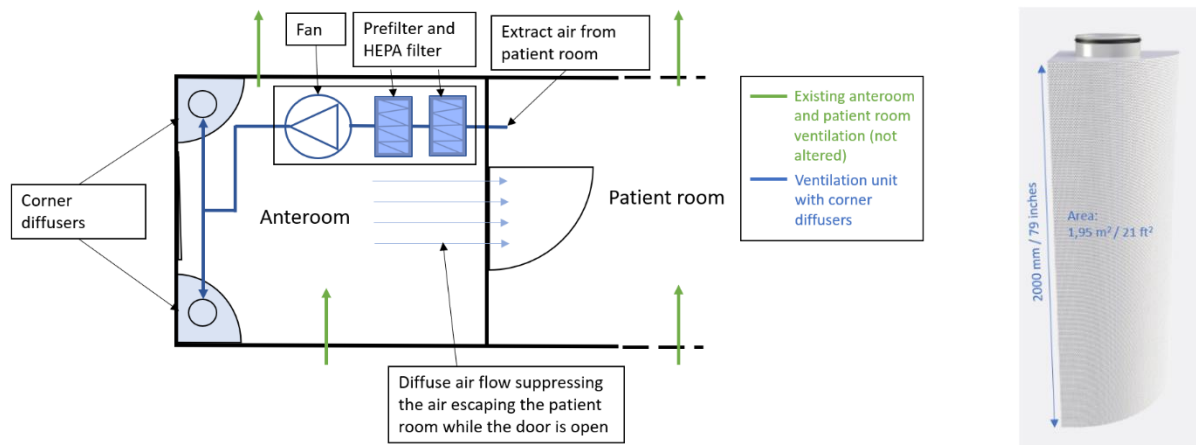

Figure 1: The idea for designing simplified AIIRs is to install a ventilation unit (blue) into a normal patient room without changing the existing patient room or anteroom ventilation (green). The unit recirculates filtrated air from the patient room and applies it to the anteroom trough corner diffusers. The large area of the corner diffusers results in a low velocity diffuse air flow towards the patient room door.

The system is intended to start in synchronisation with the movement of the door, i.e. using the same signals as the door operator. Patient room air is extracted through an exhaust grill situated in the patient room wall facing the anteroom. The air is then filtered through a prefilter and a HEPA filter and supplied to the anteroom through two large corner diffusers situated on both sides of the door facing the corridor. The area of each diffuser is 1.95 m² (21.0 ft²). The desired effect is to achieve a diffuse air flow, with the necessary velocity across the open door area, to suppress the air escaping the patient room when the door opens and someone is passing through. Three different recirculated air flow rates were tested, respectively, 300 L/s (10.6 ft³/s), 500 L/s (17.7 ft³/s) and 1000 L/s (35.3 ft³/s). The idea was tested using both CFD simulations and laboratory experiments. The focus at this stage has been on proof of concept. The results were compared to the baseline cases, where no diffusers were present.

CFD Simulations

The main goal of the CFD simulations was to represent the flows induced by the movement of the hinged door and the person passing through the doorway, in addition to the ventilation systems. To achieve this the "Overset mesh method" available within the framework of the commercial CFD code ANSYS Fluent was used. The background for the choice of this simulation method has been detailed in the paper (Harsem, et al., 2018) where it is argued that it is the most flexible and accurate way currently available for such a simulations.

In the overset mesh approach the changing geometry throughout the simulation is modelled using separate meshes for the "background" (rooms, ventilation inlets and exhausts etc.) and the moving objects (door and person). The different meshes are combined during run time by the code using special handling in the regions where they overlap. Figure 2 shows the resulting mesh structure at a specific time during the passage. The original extent of the different meshes is marked with solid lines, whereas only the coloured cells are active in the simulation. To the right the mesh of the person is shown.

All the meshes were hexahedral with cut cell refinements. Cell counts were 3.7 million for the background mesh containing the two rooms, and respectively 1.1 million and 400,000 cells for the overset meshes of door and person. Please note that although it should be possible to mimic individually moving limbs etc. with the Overset Mesh method (using one mesh for each body part) – it was chosen to implement a simpler "sliding" and rigid body motion representation of the person at this time.
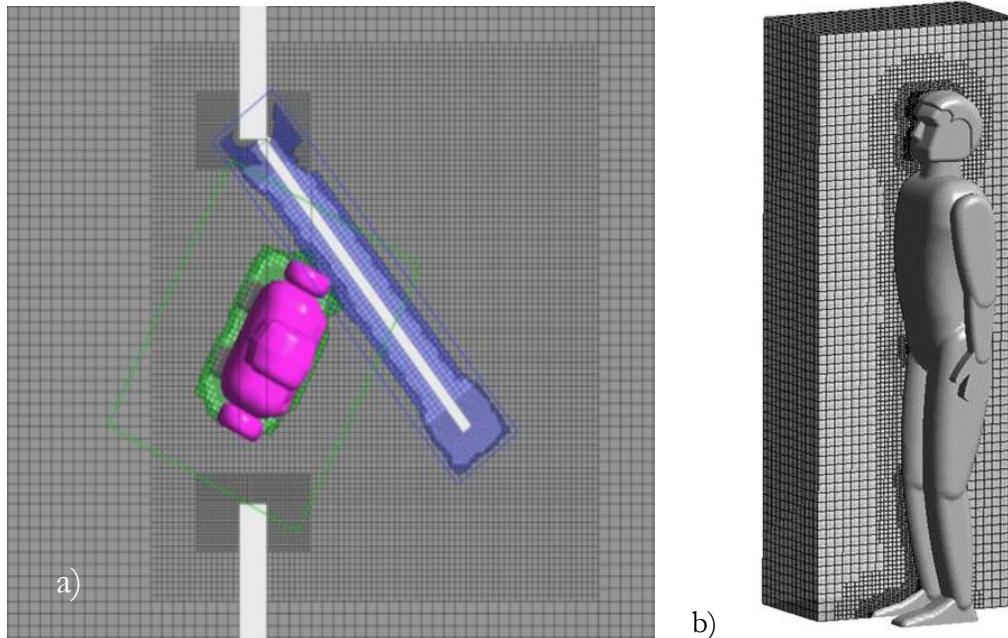

Fig.2. a) Active cells for background mesh (grey), mesh around door (blue), and mesh around the person (green), during passage through the door. b) Model of the person.

Laboratory Experiments

As in the baseline cases, tracer gas measurements were carried out in a full-scale test chamber to quantitatively assess the air volume exchange between the patient room and the anteroom generated by the door opening and passage. However, the the actual ventilation unit could not be installed in the laboratory since a HEPA filter will not filtrate tracer gas. Testing the actual unit would make it impossible to differentiate between the tracer gas (SF6) transferred due to door opening and due to reciculation. Instead, an alternative ventilation design was built as illustrated in Figure 3 below.

Tracer gas was continuously supplied to the existing supply air duct of the patient room and the tracer concentrations were measured from the exhaust in both rooms. It was ensured that the tracer concentration had reached steady state before any door openings were carried out. An actual person (as opposed to a manikin) entered and exited the rooms and the door was opened and closed by an automatic door operator while the valves were manually shifted. The valves were opened 1-2 s prior to door opening, and closed 1-2 s after the door was closed. A photo acoustical infrared gas analyzer (Gasera ONE, Gasera, Finland) measured the tracer concentrations in the exhausts. The air volume exchange was calculated in the same way as in the baseline cases, i.e. by integrating the area under the tracer gas decay curve in the exhaust and multiplying it with effective exhaust flow rate in the existing room ventilation. The area under each decay curve was calculated in two parts: the measured part and a curve-fitted part that estimated the concentration decay tail. The curve-fitted part of the previous opening was treated as background concentration and was subtracted

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from the measured concentration curve. A more detailed description of the experimental methods can be found in Harsem et al. (2018). The air volume transfer was calculated as:

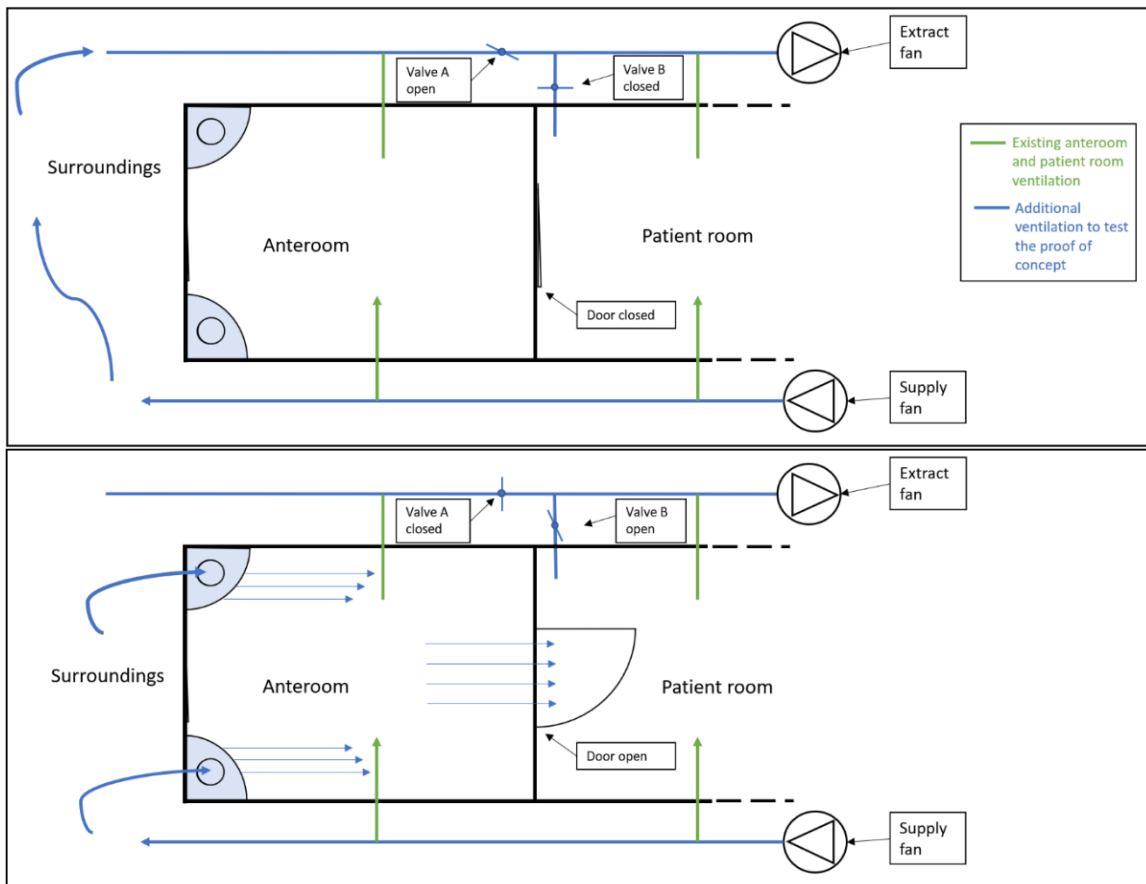$$V = Q_{eff} \frac{\int_0^\infty C_e(t)dt}{C_0}, \qquad (1)$$

Figure 3   Schematic of the laboratory layout. The green lines represent the existing ventilation which were the same as in the base line case. The blue lines represent the additional ventilation to create a directional air flow through the anteroom and doorway. (a) Valve A is open, Valve B is closed. The air supplied to the surroundings are exhausted without entering the laboratory (b) Valve A is closed, valve B is open. The air supplied to the surroundings is forced trough the corner diffusers when the door between the anteroom and the patient room is open.

RESULTS AND DISCUSSION

Figure 4 (a-b) contains four pictures from the CFD simulations of a person exiting the patient room towards the anteroom. The picture series illustrates what is happening when the diffuse air flow from the corner diffusers in the anteroom is increasing. Figure 4a is from the baseline case, i.e. without any directional air flow. The picture shows how a relatively large air volume is transferred into the anteroom due to both the door opening itself and from the wake produced by the moving person. Figure 4b is taken at the exact same moment during the passage, but now with a 300 L/s (10.6 ft³/s) air flow barrier. The picture shows that the door induced flow is suppressed by the air flow barrier.

However, the wake behind the person is still quite strong. In Figure 4c, with 500 L/s (10.6 ft³/s), it seems like the door induced flow is completely suppressed. Instead, clean air is pushed in to the patient room. The wake behind the person seems to be significantly reduced, but some air is still transferred to the anteroom. Figure 4d shows how almost all air transfer from patient room to anteroom is removed when applying a diffuse air flow of 1000 L (35.3 ft³).

The resulting air exchange are summarized in Table 1. The average air transfer in the baseline cases, i.e. a normal patient room with balanced ventilation, was 781 L (27.6 ft³) in the CFD simulations and 729 L (25.7 ft³) in the laboratory experiments. In other words, a relatively large amount of potentially contaminated air was transferred to the anteroom.
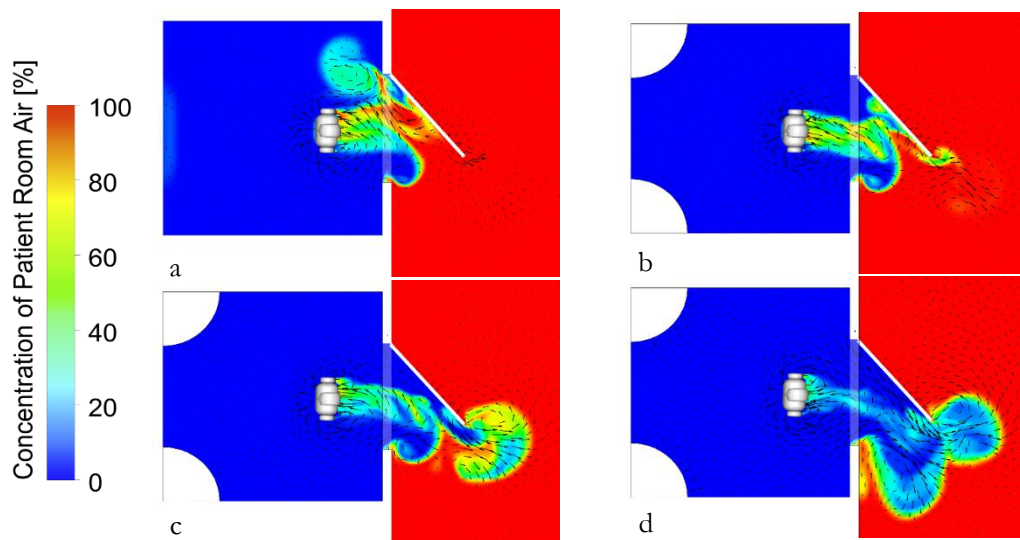

Figure 4: CFD simulations of a person entering the anteroom. (a) Baseline case without air flow barrier. (b) Case 1: 300 L/s (10.6 ft³/s) air flow. (c) Case 2: 500 L/s (17.7 ft³/s) air flow (d) Case 3: 1000 L/s (35.3 ft³/s) air flow.

Case 1 is the simulation and experiments with 300 L/s (10.6 ft³/s) of air exhausted from the patient room, filtrated through HEPA filters and supplied back to the anteroom through corner diffusers. The simulated effect of this diffuse air flow was 223 L (7.9 ft³) of transferred air in the CFD simulations, or a 71 % reduction compared to the baseline case. The corresponding number for the laboratory experiments was even lower, resulting in an average of 187 L (6.6 ft³) of transferred air when a person exited the patient room, or a 74% reduction. In case 2, 500 L/s (17.7 ft³/s) diffuse air flow was applied in the anteroom, resulting in an air transfer of 106 L (3.7 ft³) in the CFD simulations and 148 L (5.2 ft³) on average in the laboratory experiments. In other words, the CFD simulation showed a reduction of about 86% compared to the baseline cases. The reduction in the laboratory experiments was 80%.

Table 1.   Air Transfer – Exiting the Patient Room

Test cases	Flow in diffusers [L/s] / [ft³/s]	Air Transfer	
		CFD simulations [L] / [ft³]	Laboratory Experiments [L] / [ft³]
Baseline case	0.0 / 0.0	781 / 27.6	729 / 25.7
Case 1	300 / 10.6	223 / 7.9	187 / 6.6
Case 2	500 / 17.7	106 / 3.7	148 / 5.2
Case 3	1000 / 35.3	29 / 1.0	111 / 3.9

When doubling the air volume flow in case 3, i.e. to 1000 L/s (35.3 ft³), the resulting air transfer was 29 L (1.0 ft³) in the CFD simulations, equivalent of a reduction of 96% compared to the baseline cases. In the laboratory experiments, the air transfer was a noticeably higher, but the results still showed an 85% reduction of transferred air. The average air transfer due to opening the door and passage in the laboratory experiment for case 3 was 111 L (3.9 ft³).
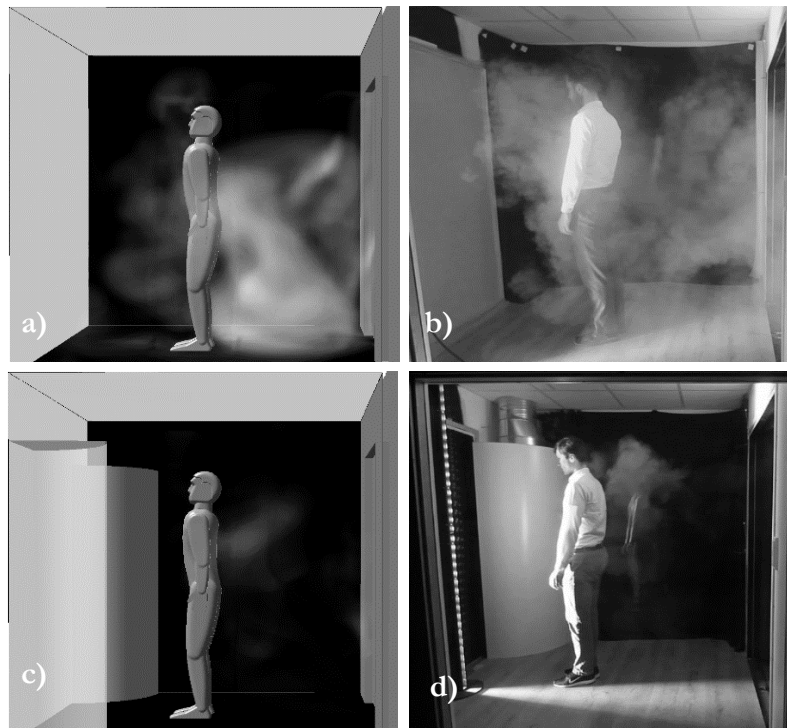

Figure 5: (a) Volume rendering of smoke from CFD simulation of the baseline case without air flow barrier. (b) Smoke vizualisation in the laboratory of the baseline case without air flow barrier (c) Volume rendering of smoke from CFD simulation of 1000 L/s (35.3 ft³) diffuse air flow (d) Smoke vizualisation in the laboratory of 1000 L/s (35.3 ft³/s) diffuse air flow.

The results are also vizualised in Figure 5, this time comparing the CFD simulations and smoke vizualisation in the laboratory. The pictures are taken from the anteroom side, showing the moment after the person exiting the patient room comes to a complete stop. The upper two figures represent the baseline case while the lower two figures represent case 3 with the 1000 L/s (35.3 ft³) air flow through the corner diffusers situated on the left side in the pictures. The visualizations illustrate how significant the reduction of transferred air from the patient room to the anteroom is when the air flow barrier is applied.

This paper has focused on the proof of concept, and the results show that it is possible to suppress the air exchange caused by door opening and passage. The next step is building a protoype and testing it in a real patient room. The unit will be installed in the anteroom so that maintenance can be done with ease. The rooms might have a different layout, different background ventilation (VAV or CAV) and other locations for the existing air supplies and exhausts. As the fan only operates when the door is open, these differences are expected to have minor effects on the results. Timing of the door opening and fan operation can, however, possibly affect the existing ventilation air flows or create

a higher pressure in the anteroom relative to the corridor and the patient room for a short period. This issue might, if found to be a problem, be solved by e.g. installing pressure stabilizers between the anteroom and the patient room.

CONCLUSION

This paper proposes a design for simplified airborne infection isolation rooms (AIIRs) by installing a ventilation unit into a normal patient room without altering the existing ventilation. The idea was established after the baseline cases, performed as part of this research study, showed that door opening and passage seemed to be a major factor for contamination risk. In the baseline cases, door opening and exiting the patient room, lead to an air transfer of up to 781 L (27.6 ft³) of potentially contaminated air. Instead of high air exchange rates in the individual rooms and emphasis on the dilution of air, the simplified solution focuses on air flow patterns and air velocities. The idea is to install a ventilation unit that recirculates a large air volume from the patient room to the anteroom through low velocity corner diffusers while the door is open and someone passes through. CFD simulations and laboratory experiments show that the diffuse air flow can result in up to 85-96% reduction of air transfer compared to the baseline cases. This will enable hospitals and other healthcare facilities to be better prepared for future pandemics, and also meet the current challenges to limit the spread of airborne diseases.

ACKNOWLEDGMENTS

REFERENCES

Folkehelseinstituttet & Sosial- og helsedirektoratet. The Norwegian Isolation Guidelines, 2004. Available at: https://www.fhi.no/globalassets/dokumenterfiler/rapporter/2009-og-eldre/isoleringsveilederen.pdf

Heymann, D. L. (2007). *The world health report 2007: a safer future: global public health security in the 21st century*. World Health Organization. Available from: https://www.who.int/whr/2007/whr07_en.pdf?ua=1 [accessed November 2018].

Hayden, C. S., Johnston, O. E., Hughes, R. T., & Jensen, P. A. (1998). Air volume migration from negative pressure isolation rooms during entry/exit. *Applied Occupational and Environmental Hygiene*, *13*(7), 518-527.

Harsem, T. T., Lind, M. C., Venås, B, Kalliomäki, P., Koskela, H (2018). *Door and Passage Induced Air Exchange Across Hinged Door*. Presented at the RoomVent and Ventilation 2018 Conference in Espoo, Finland.

Harsem, T. T., Venås, B, Vikan, A. W., Lind, M. C., Kalliomäki, P., Koskela, H (2018). *CFD Simulations of Door and Passage Induced Air Exchange Across Hinged Door*. Presented at the 39th AIVC conference in September 2018 in Antibes, France.

Hyttinen, M., Rautio, A., Pasanen, P., Reponen, T., Earnest, G. S., Streifel, A., & Kalliokoski, P. (2011). Airborne infection isolation rooms–a review of experimental studies. *Indoor and Built Environment*, *20*(6), 584-594.

Khan, K., Eckhardt, R., Brownstein, J. S., Naqvi, R., Hu, W., Kossowsky, D., ... & Sears, J. (2013). Entry and exit screening of airline travellers during the A (H1N1) 2009 pandemic: a retrospective evaluation. *Bulletin of the World Health Organization*, *91*, 368-376.

Kalliomäki, P, Saarinen, P, Tang, J W, and Koskela, H. (2016). Airflow patterns through single hinged and sliding doors in hospital isolation rooms – Effect of ventilation, flow differential and passage. Building and Environment, 107, pp 154-168.

Saarinen, P, Kalliomäki, P, Koskela, H, and Tang, J W. (2017). Large-eddy simulation of the containment failure in isolation rooms with a sliding door – An experiemental and modelling study. Building Simulation, https://doi.org/10.1007/s12273-017-0422-8.

The Norwegian National Health Preparedness Plan, 2014. Available at: https://www.regjeringen.no/contentassets/c0e6b65e5edb4740bbdb89d67d4e9ad2/nasjonal_beredskapsplan_pandemisk_influensa_231014.pdf