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Published in:

Proceedings of 11th REHVA World Congress and the 8th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings

Publication date:
2013

[Link back to DTU Orbit](#)

Citation (APA):

Bolashikov, Z. D., Melikov, A. K., & Barova, M. (2013). Exposure to Exhaled Air from a Sick Occupant in a Two-Bed Hospital Room with Mixing Ventilation: Effect of Posture of Doctor and Air Change Rate. In Proceedings of 11th REHVA World Congress and the 8th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings [ID 378]

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Exposure to Exhaled Air from a Sick Occupant in a Two-Bed Hospital Room with Mixing Ventilation: Effect of Posture of Doctor and Air Change Rate

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Abstract

Full-scale measurements were performed in a climate chamber set as a two-bed hospital room, ventilated at 3, 6 and 12 ACH with overhead mixing ventilation. Air temperature was kept constant at 22 °C. Two breathing thermal manikins were used to mimic a sick patient lying on one side in one of the beds and a doctor. A thermal dummy mimicked an exposed patient lying in the second bed. The doctor either stood up or sat in a chair 0.55 m facing the sick patient. The 'sick patient' was exhaling through the mouth and inhaling from the nose. Tracer gas (R 134A) was mixed with the exhaled air to mimic airborne droplets and droplet nuclei of less than 5 µm aerodynamic diameter. Important finding of this study is that airflow distribution and interaction in rooms, position of the recipient with respect to the source, etc. may have greater impact on the exposure to exhaled air by a sick patient than the ventilation rate itself. Furthermore, increase in ventilation may affect adversely the exposure to exhaled air and thus enhance the risk from airborne cross infection.

Keywords - component; formatting; style; styling; insert (key words)

1. Introduction

Good ventilation is needed indoors to supply clean air for the occupants and to remove the generated contaminants. Among the contaminants released indoors of greatest concern are those that can cause adverse health effects. These include airborne pathogens, which when inhaled or in contact with mucosal tissue (eyes or mouth) can initiate disease in the host. The main source of airborne pathogens indoors is the occupants themselves. People generate droplets of saliva carried by expelled air when breathing, speaking, coughing, sneezing or singing [1, 2, 3]. Two ranges of particles were reported by [4]: large particles with geometric mean and geometric standard deviation of 160 µm and 1.7 µm respectively and small particles with

geometric mean and geometric standard deviation of 9.8 μm and 9 μm . Upon release the large particles evaporate slower and travel less in air before settling on surfaces indoors [5] compared to the range of small particles. . Shortly after release the generated particles evaporate and form nuclei with diameters almost half of their initial size [4]. The evaporation of generated respiratory particles as well as their spread indoors depends on the initial velocity of the respiratory jet and the ambient conditions (i.e. background velocities, air temperature and relative humidity [5]. Therefore in conditioned occupied spaces the use of ventilation plays role on the spread and deposition of the particles. This is especially important in hospital environment where the concentration of sick and infective individuals is high. Therefore good ventilation design plays an important role for controlling the spread of airborne diseases [6, 7, 8]. However, ventilation in hospital facilities may fail to successfully and fully evacuate the pathogens from the air and may result in further increase of airborne disease spread within the building envelope [9, 10, 11]. This becomes problematic especially when the health of medical staff members and visitors is at risk. Furthermore the consequence can be uncontrolled spread of the disease that can result in epidemic.

This paper presents study on exposure of a medical staff member and a second patient to exhaled air from a sick lying occupant in a two-bed hospital room. The impact of the posture of the doctor (standing or sitting) under three different levels of the background mixing ventilation (3, 6 and 12 ACH) on the spread of the exhaled air from the sick patient is measured and discussed.

2. Method

Experiments were designed and performed in a climate chamber with dimensions 4.75 m x 4.65 m x 2.60 m (W x L x H) furnished to simulate a two bed hospital isolation room. The distance between the beds was set to 1.3 m. Five ceiling-mounted light fixtures (6 W each) provided the background lighting. The chamber was located in a larger hall, where the temperature was kept constant and equal to the air temperature in the test room. A dressed thermal manikin (1.02 Clo) with realistic body size, shape and surface temperature distribution was used to resemble a “doctor” standing or sitting next to one of the two beds: 0.55 m away. The doctor was facing the sick patient. The manikin consisted of 17 sections. A second thermal manikin of 23 body segments was used to simulate a sick patient lying in the bed closest to the doctor. The manikin was dressed with patient pajamas of 0.38 Clo. The manikin was equipped with an artificial lung [12] to simulate a breathing sick patient. One full breathing cycle consisted of three steps and lasted 6 s: inhalation – 2.5 s, exhalation – 2.5 s and break – 1 s. The characteristics of the breathing cycle were: inhalation nose, exhalation mouth at tidal flow rate of 0.24 L/s (6 L/min) [13]. Each manikin released

60 W sensible heat load on average. A heated dummy with simplified body geometry was used to mimic the second patient lying in the other bed. The total generated heat power from the dummy was 60 W. The two beds were placed in parallel. The layout of the set-up is shown in Fig. 1.

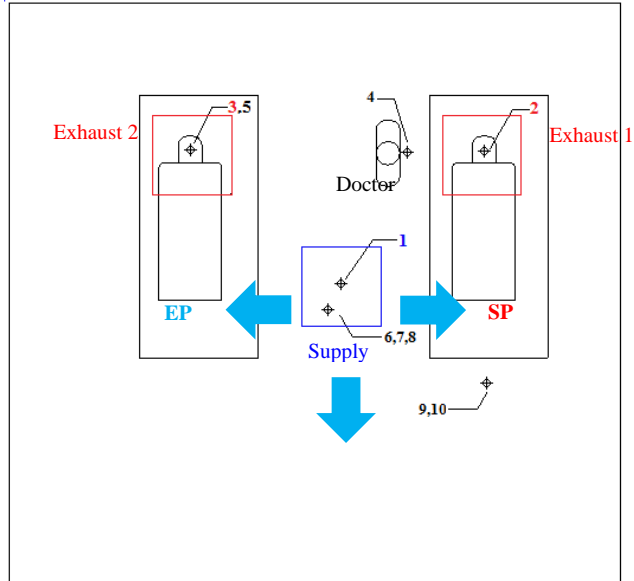


Fig. 1 Experimental set-up and locations of the sampling points for the tracer gas concentration measurements; top view: sick patient (SP), exposed patient (EP), 1 – supply, 2 – exhaust over SP, 3 – exhaust over EP, 4 – mouth of SP, 5 – mouth of EP, 6 – centre of the room 1.7 m above the floor, 7 – centre of the room 1.1 m above the floor, 8 – centre of the room 0.1 m above the room, 9 – at feet of EP1 1.7 m above the floor, 10 – at feet of EP1 1.1 m above the floor

During all experiments overhead mixing ventilation was used. The supply air was 100% outdoor air with no recirculation. The supply diffuser was a square diffuser with an unperforated face plate and with a 3-way-discharge. Two square ceiling mounted diffusers with perforated face plate were used for exhausting the air from the room. They were located above the heads of the patients. The exhausted air was equally balanced between the two diffusers.

The experiments were performed at 3, 6 and 12 ACH for both positions of the doctor, i.e. standing or sitting near the head of the sick patient 0.55 m away. Room temperature was kept at 22°C, while the relative humidity was not controlled but was measured to be between 30% and 40% during all experiments. Temperature and flow rate of supply and exhaust gas air,

temperature inside the test room as well as the amount of air exhausted were recorded and controlled constantly to keep the set values.

During all experiments R 134A tracer gas was used. It was dosed in the air exhaled by the breathing thermal manikin used to simulate the sick patient. The dosed concentration of tracer gas was kept the same for all tested cases. The tracer gas was used to simulate airborne droplets and droplet nuclei of less than 2 μm aerodynamic diameter [14] that may carry one or many pathogens. The exhaled air from the manikin (doctor) was also heated to ensure a density close to that of air exhaled by a human being. In order to avoid transport of tracer gas (R 134A) from the surrounding hall, the experimental chamber was kept slightly over-pressurized at 1.6 ± 0.2 Pa during all measurements.

The tracer gas concentration was measured with two sets of multi gas sampler and analyzer based on the photo acoustic principle at 10 points: 1) in ventilation supply, 2) in exhaust over sick patient (SP), 3) in exhaust over the exposed patient (EP), 4) at the mouth of the doctor, 5) at the mouth of the exposed patient, 6) at the centre of the room 1.7 m above the floor, 7) at the centre of the room 1.1 m above the floor, 8) at the centre of the room 0.1 m above the floor, 9) close to the feet of the sick patient 1.7 m above the floor, 10) close to the feet of the sick patient 1.1 m above the floor, Fig. 1. Neither the manikin simulating the doctor nor the heated dummy (exposed patient) was breathing. The sampling tube of R 134A was placed at the mouth 0.005 m away. As reported in the literature the tracer gas concentration measured in this way is equal to the tracer gas concentration in the air inhaled by the breathing thermal manikin [12].

2.1. Experimental Procedure

At the start of the experiments both thermal manikins and the dummy were switched on. The doctor was either standing upright or was sitting in a chair. All measurements commenced after steady-state conditions were achieved, i.e. steady concentrations at centre of room and in both TV exhausts (located at the ceiling). After reaching a steady state, 15 sampled values for each measurement point were acquired.

Temperature was measured throughout the experiments and after that a mean value was calculated for all the measurement locations.

2.2. Analyses of Results

The obtained tracer gas concentration data were normalized to the reference value of 3 ACH:

$$\varepsilon = (C_m - C_s) / (C_{m(3ACH)} - C_{s(3ACH)}) \quad (1)$$

C_m – concentration acquired in the measuring location

C_s – concentration acquired in total volume ventilation supply

$C_{m(3ACH)}$ – concentration in the measuring point at 3ACH (without headset)

$C_{s(3ACH)}$ – concentration in the total volume ventilation supply at 3ACH (without headset)

3. Results

Figure 2 shows the results from the measured concentrations normalized to the concentrations obtained at 3 ACH under mixing ventilation with the doctor standing 0.55 m away from the head of the sick patient. The sick patient was breathing sideways.

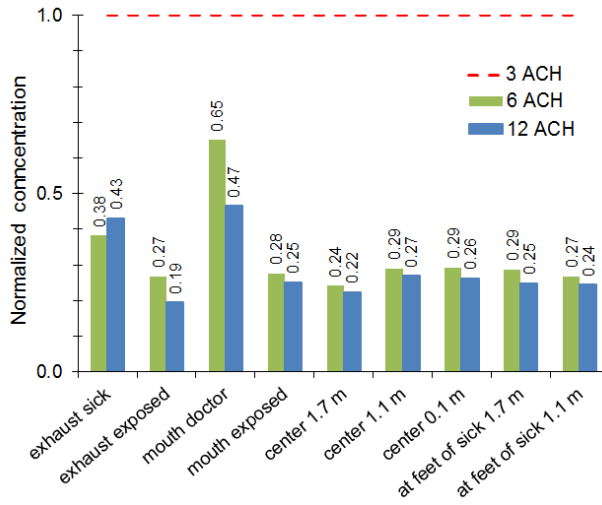


Fig. 2 Normalized concentration for 6 and 12 ACH when doctor is positioned standing 0.55 m away from the head of the sick patient (breathing sideways)

The results for 6 and 12 ACH were much lower than 1 which means that the exposure to exhaled air was reduced. However, the difference between the results for the two conditions of 6 and 12 ACH wasn't substantial. Exceptions were the results for the mouth of the doctor and the exhaust over the exposed patient, which were much higher for 6 ACH compared to 12 ACH.

As seen from Figure 2 the concentration measured at the mouth of the doctor showed approximately 35% reduction in the exposure to exhaled air at 6 ACH and 53% at 12 ACH compared to that at 3 ACH. The high values measured at the mouth of the doctor are due to the close distance between the doctor and the sick patient. Since the patient was breathing sideways, the warm exhaled air hit the abdominal part of the doctor, rose upwards with the convective flow around the doctor's body and easily reached the breathing

zone. The high values measured at the mouth of the doctor are due to the close distance between the doctor and the breathing patient. Since the patient was breathing sideways, the warm exhaled air hit the abdominal part of the doctor, rose upwards with the convective flow around the doctor's body and easily reached the breathing zone. The measured concentration at the breathing zone of the exposed patient, lying in the second bed, was decreased by more than 70% when the ventilation was increased from 3 ACH to either 6 or 12 ACH. Similar effect was found for the other room locations as well, i.e. the measured concentration levels decreased with approximately 70% compared to that at 3 ACH. However, at 12 ACH the reduction of measured concentrations in the other locations in the room was not significant relative to 6 ACH. Although twice as much air was supplied, the concentrations measured in the room at 12 ACH decreased with approximately 10% compared to 6 ACH. However, the concentrations obtained at the measurement points in the room for each tested air change rate were more or less the same which means that the exhaled air was well mixed with the room air.

The concentration level at the exhaust over the sick patient at 12 ACH was slightly higher than that measured at 6 ACH. Performed visualizations (not reported here) showed the formation of recirculation zone above each bed. The recirculation zone formed above the bed of the sick patient was with higher velocities at 12 ACH (0.3 m/s on average) compared to 6 ACH (0.18 m/s on average); velocity measurements are not reported here. The exhaled air was pushed up at higher speed towards the exhaust and this resulted in the slightly higher concentration levels registered at 12 ACH.

Measurements were performed when the doctor was seated in a chair near the head of the sick patient (0.55 m away) at 3, 6 and 12 ACH. In Figure 3 are presented the measured concentrations under the three different ventilation rates normalized to the concentrations obtained for 3 ACH under same other conditions.

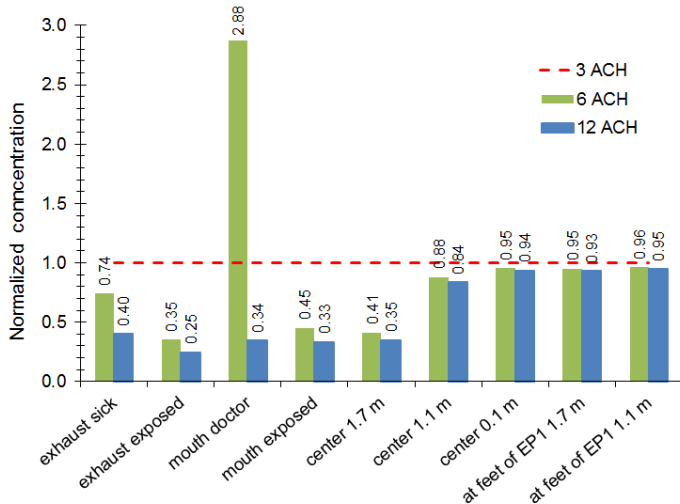


Fig. 3 Normalized concentration for 6 and 12 ACH when doctor is positioned sitting 0.55 m away from the head of the sick patient (breathing sideways)

The concentrations obtained follow the same pattern as when the doctor was standing; i.e. the higher the air change rate, the lower the concentration measured. All concentrations measured at all locations but the mouth of the seated doctor were below the concentration level for that location at 3 ACH. At 6 ACH the exposure of the doctor to exhaled air was nearly 3 times as much as under 3 ACH. The mouth of the seated doctor was approximately 1.1m from the floor on the same level as the mouth of the sick breathing patient. The airflow pattern played significant role on the exposure to exhaled air. The existing recirculation zone above the bed of the sick patient pushed the exhaled air directly into the doctor's breathing zone at 6 ACH (based on visualization study not reported here). At 12 ACH the elevated air velocities pushed the exhaled air past the doctor and into the room. The concentration measured at the breathing zone of the exposed patient was reduced by 55% at 6 ACH and 67% at 12 ACH. The recirculation zone above the bed of the exposed patient helped mix the exhaled air with clean supply air and reduce the concentration.

The difference between the results for the two conditions of 6 and 12 ACH wasn't substantial for the other measurement locations. At some locations (at the feet of the sick patient and in the center of the room at 0.1 and 1.1 m height) the concentration level at 6 and 12 ACH was very close to that at 3 ACH. Again the results can be explained by the air distribution pattern. The recirculation zone above the bed of the patient pushed the exhaled air towards the center of the room.

4. Discussion

The present study investigated on the effect of the posture of the doctor under three ventilation levels (3, 6 and 12 ACH) on the exposure to exhaled air from an infected lying occupant. The exposure of the doctor when standing near the head of the sick patient was much higher compared to the concentration measured in the room. The exposure of the doctor to the exhaled air decreased by not more than 53% at 12 ACH compared to 3 ACH. However 53 % reduction in exposure was achieved by 400 % increase in ventilation! Elevating the ventilation rate from 3 ACH to 6 and 12 ACH reduced the concentration of exhaled air measured in the room with approximately 70%. Further increase from 6 to 12 ACH resulted in minor decrease in exposure to exhaled air in the room: the concentrations measured in the selected room locations as well as at the mouth of the exposed patient were slightly lower at 12 ACH than at 6 ACH. Similar findings were documented by [15].

When the doctor was seated near the patient, the concentrations were higher than for the case when standing. In this case the mouth of the doctor was at the same height with the mouths of the two patients. The airflow pattern played a significant role on the exposure of the doctor when seated by the head of the sick patient. The formed recirculation zone above the bed of the sick patient (from a separate visualization study not presented here) helped push most of the exhaled air into the face of the seated doctor when the mixing ventilation was operated at 6 ACH.

The posture of the doctor (standing or sitting by the head of the sick patient) clearly had a significant effect on the exposure to exhaled air in the room. Also it was noticed that for the measurement locations at the feet of the sick patient and at the center of the room (0.1 m and 1.1 m heights above the floor) the concentrations measured were nearly the same at all three air change rates tested. The reason again is the airflow distribution pattern in the room. The recirculation zone above the bed of the sick patient moved the exhaled air towards the feet of the lying sick patient and the center of the room.

The exposure of the second patient wasn't influenced by the position of the doctor, Fig 2 and 3.

It can be concluded that for breathing cases the increase of ventilation rate from 3 ACH to 12 ACH caused decrease in the concentration level of exhaled air, however it was not sufficient to reduce the exposure, especially for the occupants standing or sitting near the source and aligned with the exhaled jet trajectory.

The present results confirm the findings of recent studies that elevated ventilation rates corresponding to up to 12 ACH are not sufficient to protect the medical staff and the exposed patients from airborne exposure to exhaled air by a sick occupant [16, 17]. These studies investigated the exposure to only one source, i.e. one sick patient. In case of pandemics, the density of the

patients in wards will be higher than usual and consequently the risk of airborne cross infection would rise significantly. Relying only on total volume ventilation to effectively dilute the contaminated air and reduce the risk of cross infection is not enough and may not be possible. For example, increasing the number of sick patients to two in the same room, assuming that they both release the same amount of pathogens in the room air will require supply of twice the air to ventilate the room in order to achieve the same dilution when the patient is alone. In case of isolation double bed room this will result to 24 ACH! Hence a new approach of ventilation is needed. The ultimate goal should be to provide better indoor environment and to reduce the risk of airborne cross-infection at reduced ventilation rate by more efficient air distribution methods than the mixing air distribution used today.

5. Conclusions

The present study focused on the reduction in exposure to exhaled air by a “sick” patient lying in bed and facing a standing or seated doctor in a double bed hospital room ventilated by mixing air distribution at 3 ventilation rates: 3, 6 and 12 ACH. Based on the results obtained the following conclusions can be made:

- The posture of the doctor standing or sitting by the bed of a sick patient affected the spread of exhaled air in the room;
- The highest exposure to exhaled air for the doctor was documented at 3 ACH when standing and at 6 ACH when sitting near the head of the sick patient. Mixing ventilation alone is not efficient to reduce the exposure to exhaled air when the exposed person is very close to the sick occupant;
- The increase from 6 to 12 ACH lead to minor decrease in the background concentration level, which was not significant, suggesting that elevated dilution is not an efficient strategy to reduce the background exposure level;
- The effect of the airflow pattern may have more significant impact on the exposure of occupants to exhaled air when the exposed person is in the vicinity of the sick patient compared to ventilation rates.

6. Acknowledgement

This research was supported by the Danish Agency for Science Technology and Innovation. Project No. 09-064627.

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