Air Distribution Systems and Cross-Infection Risk in the Hospital Sector

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Published in:
Ventilation 2012

Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

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Ventilation 2012, The 10th International Conference on Industrial Ventilation, Paris, 17 – 19 September 2012.

AIR DISTRIBUTION SYSTEMS AND CROSS-INFECTION RISK IN THE HOSPITAL SECTOR

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Abstract

We protect ourselves from airborne cross-infection in our indoor environment by supplying fresh air to the room by natural or mechanical ventilation. The air is distributed in the room according to different principles as e.g. mixing ventilation, downward ventilation, displacement ventilation, etc. A large amount of air is supplied to the room to ensure dilution of airborne infection.

The paper discusses both the macroenvironment and the microenvironment. The macroenvironment is the conditions created by the air distribution system, and the microenvironment is the conditions created by the local flow around persons in combination with the surrounding conditions.

Analyses of the flow in the room (macroenvironment) show a number of parameters that play an important role in minimising of airborne cross-infection. The air flow rate to the room must be high, and the air distribution pattern can be designed to have high ventilation effectiveness. Furthermore, personalized ventilation may reduce the risk of cross-infection. Personalized ventilation can be used especially in hospital wards, aircraft cabins and, in general, where people are located at defined positions.

Analyses of the flow in the microenvironment show that a number of variables are important, as e.g. distance between people, people's posture, surrounding temperature gradients and surrounding temperature, activity level, etc.

Experiments with tracer gas simulating droplet nuclei and experiments with large particles, simulating droplets are used for the study of airborne cross-infection risk and for the study of droplet-borne transmission of a disease. CFD predictions are used to support these experiments.

Keywords: Cross-infection, air distribution, droplet nuclei, droplet, mixing ventilation, displacement ventilation, downward ventilation

1 Introduction

People spend many hours in an indoor environment and experience shows that airborne cross-infection mainly takes place in this environment as clearly proven in the worldwide SARS outbreak in 2003 (Li et al. 2004a and 2004b). It was concluded that the danger was especially pronounced in the hospital environment (Li et al. 2004a; Qian et al. 2007). The efficiency of the ventilation systems to minimize cross-infection plays an important role, and the possibility of protecting people from airborne infection was addressed in a literature review by Li et al. (2007), which concluded that there is strong and sufficient evidence of a connection between ventilation and control of air flow directions in buildings and the transmission and spread of infectious diseases such as measles, TB, chicken pox, anthrax, influenza, smallpox and SARS.

Different air distribution systems such as mixing ventilation, downward ventilation and displacement ventilation offer different possibilities in protecting people from airborne pollutants as bacteria and viruses. The pollutants are almost fully mixed in the occupied zone in a room ventilated by mixing ventilation or downward ventilation, and they are removed by a diluting process (Nielsen 2007). If the source of pollution is also a heat source, then displacement ventilation offers possibilities to work with two zones; a low zone with clean air and an upper zone with pollutants. It is possible to design a system with low exposure as discussed by Skistad et al. (2002), but in certain situations both low and high exposure may also exist in rooms with displacement flow as shown by Bjørn and Nielsen (2002) and Qian et al. (2004). Therefore, it is a general conclusion that displacement ventilation should not be used in areas where there is a risk of cross-infection, as in hospitals, Li et al. (2011).

Flow with some displacement effect and increased efficiency can be obtained in a room ventilated by ceiling-mounted diffusers with large inlet areas. The air distribution in the room is mainly controlled by buoyancy forces from the heat sources, but the flow from the terminal can be characterized as a displacement flow with a downward direction in areas without thermal load. The displacement flow, which exists in different areas of the room, may indicate the possibility of obtaining improved protection in those areas (Nielsen et al. 2007a and 2009). This system will be discussed further in this paper.

A reduction of cross-infection can be obtained by Personalized Ventilation (PV). Experiments with personalized ventilation integrated into hospital beds together with vertical ventilation from ceiling-mounted terminals show an increased efficiency of the personal protection from a factor of 5 up to 35 (Nielsen et al. 2007a, 2007b and 2008a). In general, personalized ventilation systems have been studied intensively during recent years, see (Melikov 2004; Melikov et al. 2002 and 2003).

2 Simulation of Cross-Infection

Cross-infection risk is caused by the movement of airborne particles (bacteria and viruses) in the room air flow. The experiments are carried out by tracer gas, which has the same density as the air in the room, and the results are therefore valid for situations where bacteria and viruses are transported on droplets (droplet nuclei) smaller than 5 - 10 μm. Large droplets are also part of the cross-infection process. They settle either on surfaces close to the infection source, evaporate and decrease in size and follow the air flow as droplet nuclei. Tracer gas is, therefore, particularly useful for simulation of the movement of airborne infection at large distances outside infected people's microenvironment, while CFD simulations and particles (Arizona Test Dust) can be used for the simulation of large particles.

Tracer gas or particle concentration cannot be directly used as a measure for the health risk, but it can give an indication of this risk. The health risk can be estimated from the Wells-Riley model which, among other things, links the concentration in a person's inhalation and the connected risk of infection (Riley et al. 1978; Qian et al. 2006). All the measurements and discussions in this paper are based on steady state condition; however the Wells-Riley model will also introduce time as a parameter, as e.g. the number of infected cases over a period of time. All the experiments described in this paper have been made in a test room without people in motion. The activity level of the staff will in practice have influence on the concentration distribution in the room, and it is found that mixing ventilation is considerably more robust in this respect compared with displacement ventilation, Brohus et al. (2008). Door openings can also disturb the concentration distribution in the ward, see Tang et al. (2005).

The air distribution in a room is often addressed on a *macro scale* level which means that it is only the air distribution system which controls the flow and the particle distribution in the room, see figure 1A. When persons are close to each other, the exposure can rise to a high level independent of the general contaminant level of the occupied zone. In other words, if the air distribution system is designed to make an efficient ventilation of the room, there will still be a *microenvironment* around

people close to each other, which cannot be influenced by the general air distribution system, see Figure 1B. The processes in the microenvironment will be addressed separately in this paper.

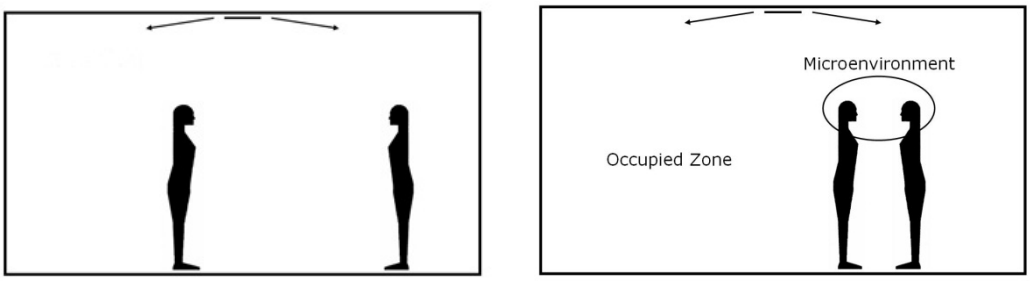

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Figure 1. *A) The flow is controlled by the air distribution system. B) The microenvironment can have a local high exposure partly uninfluenced by the air distribution system.*

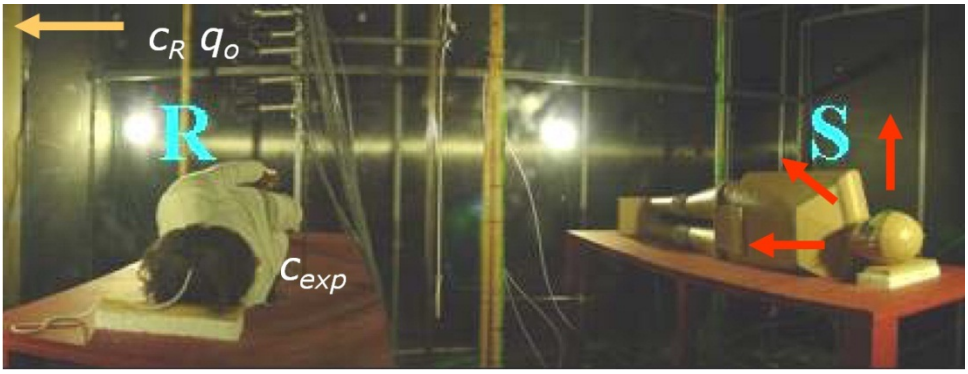


Figure 2. *Two patients (life-size manikins) in a hospital ward. One patient is the source of airborne infection (S), and the other patient is the recipient (R).*

The cross-infection process based on transport of tracer gas or particles through the *macroenvironment*, and the effect of the different air distribution systems and source level can be explained with Figure 2. The figure shows an example of a situation in a hospital ward with a source patient (manikin S) and a target patient (manikin R). The source has the level of S and represents the respiratory activity of a potentially infectious patient, or related medical procedures such as the use of nebulizer. The target patient inhales a concentration expressed by c_{exp} or $c_{exp,PV}$. The room is supplied with an air flow rate of q_o. The ventilation index at the position of manikin R's inhalation zone (exposure index) is ε_p and a personal exposure index with respect to the PV system is $\varepsilon_{\text{exp},PV}$. It is possible to show that exposure of the target person in the room c_{exp} or $c_{exp,PV}$ is equal to, Nielsen (2009):

$$c_{\text{exp}} = \frac{1}{q_o} \cdot \frac{1}{\varepsilon_p} \cdot S \qquad (1)$$

or in the case with personalized ventilation, Nielsen (2009):

$$c_{\text{exp},PV} = \frac{1}{q_o} \cdot \frac{1}{\varepsilon_p} \cdot \frac{1}{\varepsilon_{\text{exp},PV}} \cdot S \qquad (2)$$

In case of a steady state, equations (1) and (2) show that the concentration of any airborne infection from the source manikin can be reduced by:

- using high ventilation rate q_o to dilute the infected particles to a low concentration level
- having a high ventilation or exposure index ε_p in the patients' breathing zone
- working with personalized ventilation which has a high exposure index $\varepsilon_{exp,PV}$
- reducing the contaminant emission S of the source

Disturbances may, while they are occurring, reduce ε_p to a value close to 1.0. All in all, it will be most efficient to work with systems that can handle both a high flow rate and that have a high ventilation index. It will also be efficient to work with personalized ventilation and to reduce the emission source of the disease. These ideas are addressed in the following chapter.

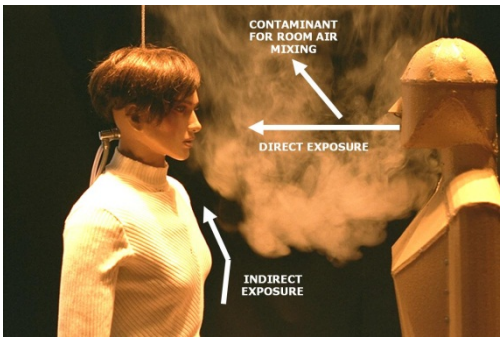


Figure 3. *Flow in the microenvironment around two persons close to each other.*

Figure 3 shows the flow of droplet nuclei around two persons located close to each other. This flow around the persons is in the microenvironment. It is slightly dependent on the air distribution system, but it is especially dependent on the local flow in the boundary layer of the persons and the exhalation flow of the persons as well as the person's position and size. The figure shows how bacteria and viruses can be directly transported in the exhalation flow and also how it can be diffused into the room air flow and then be entrained in the target person's boundary layer and transported into the breathing zone of this person.

The cross-infection risk is expressed by the local concentration in the inhalation of the target person divided with the return concentration in the room air distribution, called the exposure:

$$c^*_{exp} = \frac{c_{exp}}{c_R} \qquad (3)$$

The exposure of 1.0 corresponds to a situation with full mixing in room and microenvironment.

Parameters that influence the cross-infection risk between people situated close to each other in a ventilated room can be summarized as:

- Distances between the persons
- Positions and orientations of the persons
- Breathing process (breathing through the mouth or the nose, opening of mouth, coughing, speaking)
- Difference in the height of the persons
- Activity levels of the persons (breathing frequency, minute volume (MV), flow in thermal boundary layer)
- Number of persons
- Temperature and vertical temperature gradient in the microenvironment around the persons
- Air velocity (speed and direction) in the microenvironment around the persons
- Turbulence level of the air flow in the microenvironment around the persons

The last three points are the result of room load and type of air distribution system in the room.

3 Cross-Infection Risk in a Hospital Ward (the Macroenvironment)

Cross-infection on a macro scale can be discussed on the basis of equations (1) and (2). It can be concluded that a high ventilation rate is important as well as a high ventilation index in the patients' breathing zone. Personalized ventilation is a possibility and low emission from the source patients is of course important.

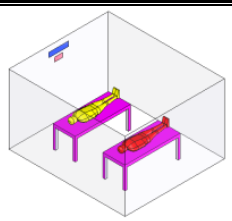
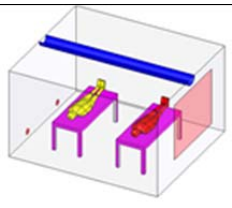
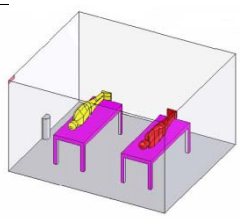
3.1 Mixing ventilation, downward ventilation and displacement ventilation

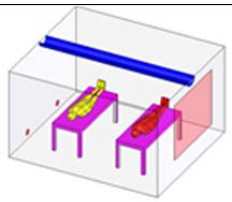
Qian et al. (2006) studied the dispersion of exhaled droplets in a two-bed hospital ward with different air distribution systems. The three first systems; mixing ventilation, downward ventilation and displacement ventilation, are from this study, see Table 1. It is not enough to look at the ventilation index, which can be obtained, but it is in fact more important to look into the maximum air flow rate which can be obtained with comfort, because the flow rate is an important parameter in reducing the concentration level. Flow rates in the hospital ward (table 1) which keep the draught below ~15 cm/s can be found from Nielsen (2007).

The mixing ventilation system shown in Table 1 will have an air change rate of 7 h^{-1} without draught while the downward ventilation will have the level of 19 h^{-1} before giving a draughty environment. The limit for the displacement ventilation system is 5 h^{-1}. These are very important differences. If, for example, the source patient continuously emits the (arbitrary) value of 3,000 droplet nuclei per second, then the concentration in the room is 40,000 droplet nuclei per m^3 in the first case, and less than 15,000 droplet nuclei per m^3 in the second case, Nielsen (2009). This emphasizes that it is important to consider the draught generated in different systems in the dimensioning of the maximum air flow rate to a room. On the other hand, we have to realize that a high air flow rate is an expensive solution.

Downward-directed ventilation systems are recommended by several guidelines for isolation rooms; see ASHRAE (2003) and CDC (1994).

Table 1. *Hospitals wards with different air distribution systems and the obtained air change rates and droplet nuclei concentration.*

Hospital ward	Air distribution system	Air change rate (h^{-1})	Droplet nuclei per volume (m^{-3})
	Mixing ventilation	7 h^{-1}	40 000
	Downward ventilation with large supply area	19 h^{-1}	< 15 000
	Displacement ventilation	5 h^{-1}	860 droplet nuclei when the source manikin is lying on the back and 86 000 droplet nuclei when the source manikin is facing the target manikin

	Downward ventilation including personalized ventilation	19 h^{-1}	< 15 000 droplet nuclei when the source patient is without a PV system and 1500 droplet nuclei when the source patient has a PV system (ventilated pillow)

The ventilation index of the target patient's breathing zone is around 1 for both mixing ventilation and downward ventilation. Displacement ventilation offers the possibility to work with two zones in a room and therefore to have a ventilation index different from 1. Qian et al. (2006) show that the displacement ventilation system offers very good protection of the target manikin from cross-infection risk when the source manikin is lying on its back. A personal exposure index of 70 is typically obtained in this case. A problem arises when the manikin is lying on its side, facing the target manikin. The temperature gradient in the room will stratify the exhalation from the source manikin, and the high concentration of tracer gas (exhalation) flows to the target manikin's breathing zone, giving a low personal exposure index of 0.7. A similar effect on the exhalation flow between two persons has also been shown by Bjørn and Nielsen (2002). This is a typical problem for displacement ventilation. It is possible to obtain a very high ventilation index, but it cannot be guaranteed that the value is preserved in all situations. It is a general conclusion that displacement ventilation should not be used in areas where there is a risk of cross-infection as in hospitals, Li et al. (2011).

3.2 Personalized ventilation

The use of a personalized ventilation system installed in beds is a new idea, which in the future may be a solution for minimizing cross-infection in isolation rooms. The personalized ventilation system should be supplemented with a general ventilation system in the room. The personalized ventilation is especially efficient if the patients are bed-bound, and the effectiveness will be reduced when they are more mobile. A system with personalized ventilation will, therefore, be more efficient at night when patients are sleeping.

A system suitable for a bed would be a personalized ventilation system which utilizes pillows, mattresses, etc. as supply openings of fresh air by using fabric as a diffuser, Nielsen et al. (2007b). The consequence of the high exposure index of the PV system means that particles in the target manikin's inhaled air can be reduced from a level of 15,000 droplet nuclei pr. m^3 in the room, as found in the earlier example with vertical ventilation, to a level of 1,500 droplet nuclei pr. m^3 ($\varepsilon_{exp,PV} \sim 10$) with a combined system. The system does protect the healthcare personnel in the hospital ward to some extent when it is used in combination with other air distribution systems.

3.3 Downward ventilation with increased ventilation index

It is interesting to see whether or not it is possible to design an air distribution system which will have the possibility of both high air change rate and high ventilation index. Equations (1) and (2) show that this will give the lowest exposure for patients close to a source patient. A downward ventilation system can have a high air change rate and a ventilation index which is higher than 1.0 when the heat loads are located at some distance from the diffusers in the ceiling as shown in Figure 4. An index larger than 1.0 is obtained because cold flows from the diffusers are separated from the warm plumes above the heat sources. The system requires a high location of the return openings as indicated by Nielsen et al. (2009).

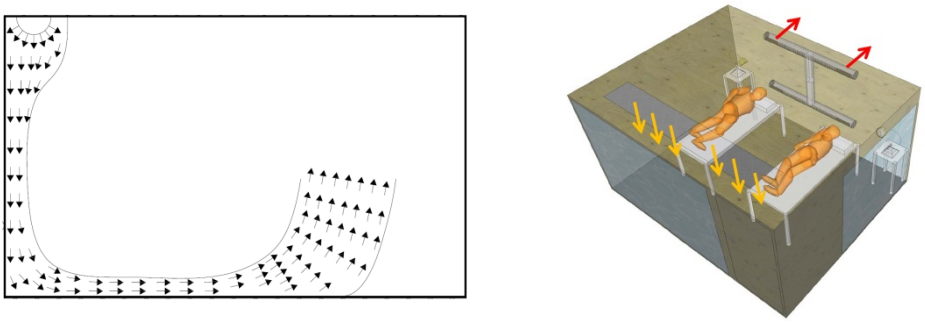


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Figure 4. *Hospital ward with a ceiling mounted diffuser and high location of return openings.*

New measurements show that the location of the return openings is very important with this type of air distribution system, Nielsen et al. (2011). Figure 5 shows the exposure index with different heights of the return openings. The index increases from 1 to 2 - 3 at increasing height. The importance of a high location is probably the possibility of reducing the contaminant level by the extract (return) flow, which in other cases would be entrained in the flow at the supply diffuser. The flow rate should always be as high as possible. A large ventilation index is often connected to the buoyant flow. The buoyancy effect is, on the other hand, decreased when a high flow rate is used, see Figure 5.

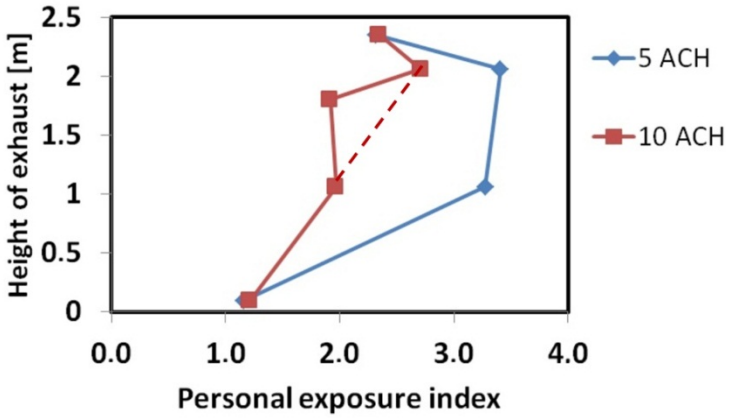

Figure 5. *Personal exposure index versus height of return opening for the room shown in Figure 4.*

The downward-directed flow indicated in the CDC recommendations will make it is possible to have a high flow rate in a room without draught, because of large supply areas in the ceiling or in the wall, as discussed earlier. This provides the possibility of working with a high dilution and thus a low level of contaminant concentration. The CDC recommendation of a low location of the return opening will not create an optimal flow, but it will be fully mixed within the room. It is a general experience that droplet nuclei should be removed by a high location of the return openings and larger droplets should be removed by cleaning floor and other surfaces. Similar results have been found by Qian et al. (2008).

4 Cross-Infection Risk between People Standing Close to Each Other (the Microenvironment)

When people are standing close to each other there is a risk of cross-infection due to the flow in the microenvironment between them. This local flow is only slightly dependent on the air distribution system via the temperature and the temperature gradient around the people, the air velocity and the

turbulence level of the flow. The primary flow in the microenvironment is the thermal boundary layer around persons and the exhalation flow from the breathing. Figure 6 shows four different methods to address this flow.

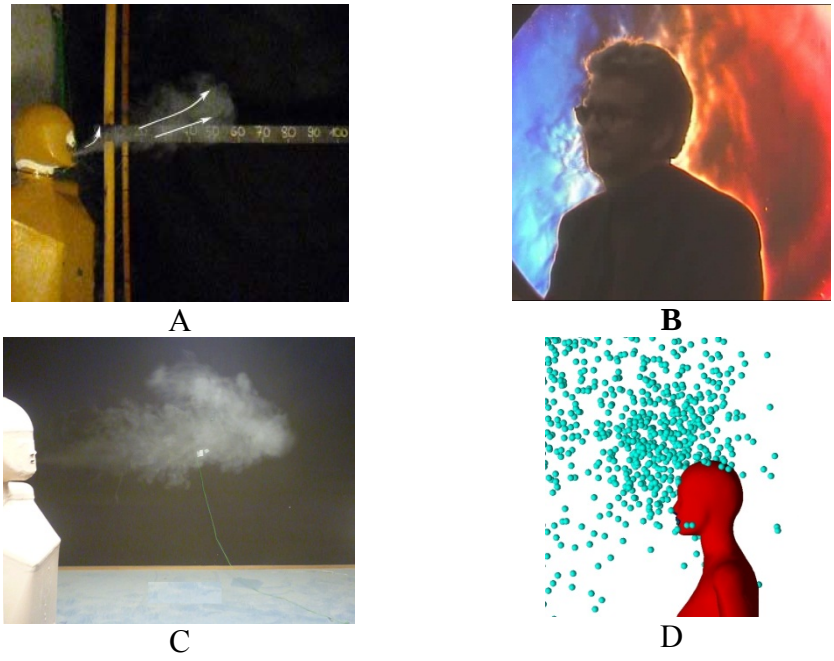

Figure 6*. Different registrations of the exhalation flow from a person or a thermal manikin. A) smoke and tracer gas, B) Schlieren image, C) large particles and D) CFD simulation with both small and large particles.*

Figure 6A depicts the flow two seconds after start of the exhalation cycle through the mouth of a thermal manikin. The direction is influenced by the thermal boundary layer around the manikin and the temperature of the exhalation as well as the temperature of surroundings. The flow can be illustrated by smoke, and the transport of bakeries and virus in the form of droplet nuclei can be studied by the use of tracer gas. This method has been used for the measurements in the figures 8 and 9. The Schlieren technique is a technique where you get an image of the temperature differences continuously moving around the person, Tang et al. (2011a and 2011b). It is very illustrative and clearly shows the boundary layer around the person and also breathing, talking and coughing. Figure 6C shows the use of Arizona Test Dust for simulation of large particles, Nielsen et al. (2012). Finally, Figure 6D show a CFD prediction with exhalation of large particle which can evaporate during the flow through the air, Liu (2011).

4.1 Flow of droplet nuclei

The flow in the microenvironment and the cross-infection risk between two persons are among other things dependent on the position of the people and the distance between them. Figure 7 shows four different positions which have been studied in the case of displacement ventilation in the room.

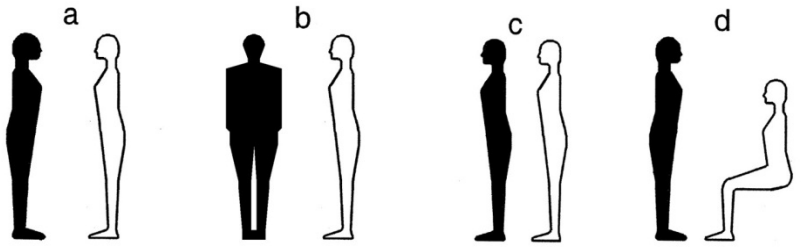

Figure 7. *Positions of manikins. a) face-to-face, b) face-to-side of target manikin, c) face-to-back of target manikin, d) seated source manikin. Source manikin is white, and target manikin is black.*

The results of the tracer gas experiments are shown in Figure 8, Olmedo et al. (2012).

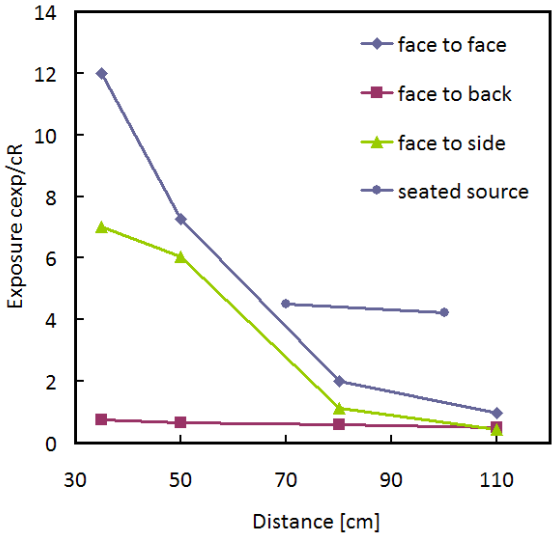

Figure 8. *Exposure of the target manikin versus distance between the two manikins in a room with displacement ventilation. Measurements for the four positions: face-to-face, face-to-side of target manikin, face-to-back of target manikin and seated source manikin. Exposure is given as* c_{exp}/c_R. *The flow (minute volume MV) is 11 l/m for the source manikin and 10 l/m for the target manikin. The source manikin has a total heat release of 94 W and the target manikin a release of 102 W. Both manikins have an exhalation temperature of 34* ^{o}*C).*

The exposure shown is given as c_{exp}/c_R. When the distance between the manikins is 110 cm, the target manikin inhales a concentration equal to the background concentration in the room (indirect exposure, see Figure 3). The two manikins do not have a common microenvironment with respect to cross-infection considerations. The concentration c_{exp}/c_R is ~0.5 for face-to-side and face-to-back, which is typical of displacement ventilation where the inhalation contains air from the lower zone in the room, Brohus and Nielsen (1996). c_{exp}/c_R is ~1.0 for the face-to-face situation, and the higher value indicates that a small fraction of direct exposure takes place at a distance of 110 cm.

There is a remarkable increase in the direct exposure when the distance between the manikins is smaller than 80 cm in the cases face-to-face and face-to-side of the target manikin. The exposure increases up to 12 times the concentration in a fully mixed situation, in the face-to-face situation, and up to 7.0 times in the face-to-side of the target manikin situation, where the distance is 35 cm. With respect to the protection against cross-infection, this is a serious setback for systems generating a vertical temperature gradient.

Protection from cross-infection seems to be high in the face-to-back situation. The exposure c_{exp}/c_R only reaches 0.75 at a distance of 35 cm, which is below a fully mixed case.

The two manikins are of the same height. People of different heights could be more or less exposed than found in Figure 8, Liu et al. (2011).

Figure 8 shows that there is a high and rather constant level of cross-infection risk in the case with a seated source manikin and a standing target manikin, where c_{exp}/c_R is equal to 4.5. The main reason for that level may be the low position of the source manikin's exhalation zone and the rising exhalation flow. Therefore, this is a situation where different heights are an important parameter. A similar situation with a high exposure from a seated manikin is shown by Bjørn and Nielsen (2002).

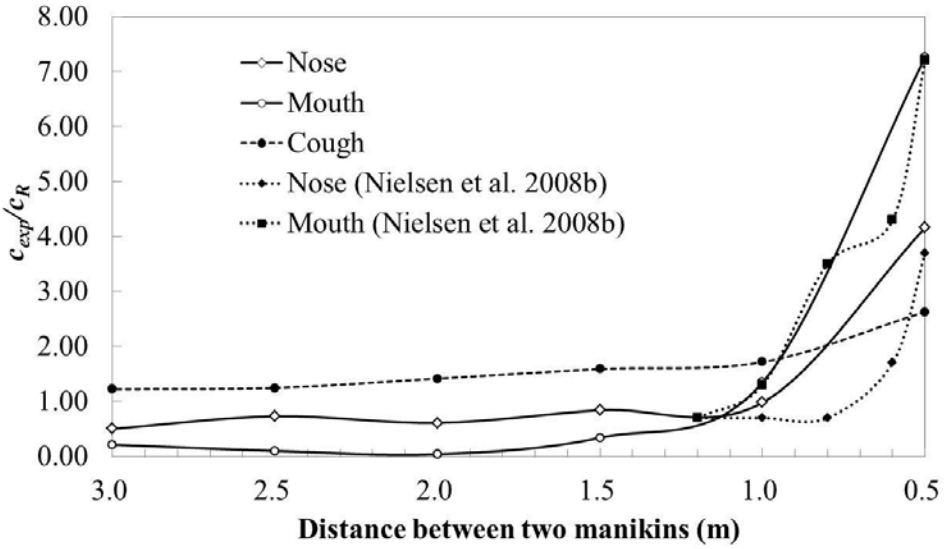

Figure 9. *Exposure of the target manikin versus distance between two manikins in a room with displacement ventilation. Results are shown for both breathing through the mouth and nose and for coughing. Results are also compared with earlier results, Liu et al. (2011).*

Figure 9 indicates that the distance between 1 m and 3 m is obviously a part of the macroenvironment without any influence of the distance between the persons. It is the air distribution system which is important in this case. It is also shown that breathing through the nose will give a large increase in the cross-infection risk when the distance between the persons is short.

The coughing is simulated by a generator that releases single airflows with high pressure with the same momentum flow as that of a real human cough measured by Kahn et al. (2004). The peak velocity is about 30 m/s. The coughing airflow reaches the target manikin much quicker than the exhalation flow, and the entrainment from the surrounding cleaner air is likewise larger than for an exhalation flow. This, and an upward direction of the flow, may explain the relative low exposure (c_{exp}/c_R) in this case, see Figure 9. The time for the target to inhale from the direct coughing jet is quite short, less than 0.5 second. It is known that a cough contains both droplet and fine particles (<5 μm). Only the fine particles can be simulated by tracer gas. Droplets are not exposed to a high diffusion as tracer gas. Therefore, a cough will probably generate a higher exposure than the one shown in Figure 9.

The highest exposure in the microenvironment is obtained when displacement ventilation is the air distribution system. Other systems as mixing ventilation, downward ventilation and even surroundings without ventilation have been tested and they show the same effect, but at a lower level, Nielsen et al. (2008b).

4.2 Flow of Large Droplets

Traditionally two transmission routes are considered, namely transmission via droplet nuclei (< 5-10 μm) and transmission via droplets (> 5-10 μm), and they correspond to two infection routes: droplet infection and airborne infection. Transmission via contact to surfaces is another important transmission route but this will not be considered here.

Experiments with large droplets are made by adding Arizona Test Dust (ISO 12103-1, A4 COARSE TEST DUST) to the breathing of a standing manikin.

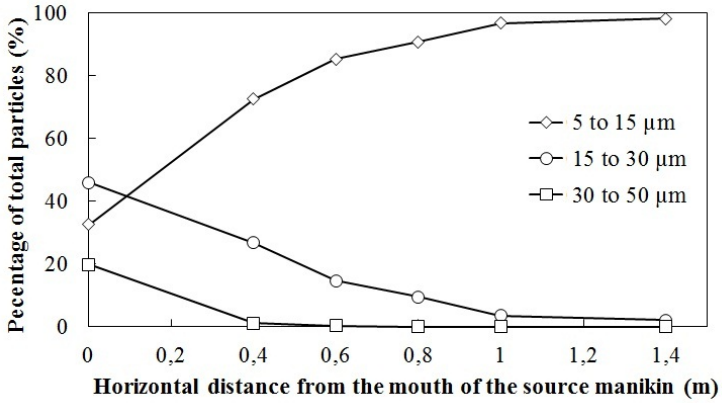

Figure 10. *Deposition of test dust on the floor in front of a thermal breathing manikin. The manikin has a heat release of 113 W corresponding to an activity level of 1.32 MET and a breathing frequency of 15 min^{-1}, Nielsen et al. (2012).*

Figure 10 shows the deposition along the floor in front of the thermal breathing manikin. Particles of the sizes 15 to 30 µm are settled within 1 m and particles of the sizes 30 to 50 µm are settled within 0.4 m. The maximum exhalation velocity is 4.3 m/s. These results are in good agreement with the expectation of a settlement within a "short" distance of 1.5 m, Lidwell and Williams (1961) and in agreement with Xie et al. (2007) who have shown that a droplet with a 100 µm can penetrate around 1 m in air with an initial horizontal velocity of 10 m/s. The distribution of particles is given in percentage of total particle number. The concentration of the sizes 5-15 µm may not be a deposition directly from the exhalation but from the room air in general, because they can be considered as droplet nuclei. The small particles are evenly distributed all over the room, and therefore it is assumed that this concentration has a constant level over the total measuring area. The figure shows that smaller particles (5 to 15 µm) will be deposited with an increasing fraction (but at a constant level) as a function of the distance from the manikin.

It should be noted that the measurements generally show that the cross-infection risk by airborne droplet nuclei may increase to a high level when people are standing close to each other (see Figures 8 and 9). Figure 10 show a similar situation connected to droplet infection, with an increased risk of infection when the distance between people is small, while the probability of infection is smaller at larger distances. Those similarities in the characteristics could make it difficult to distinguish between the two different principles of cross-infection risk (airborne transmission and droplet spread transmission) as also pointed out by Li (2009).

4.3 Flow of Droplet with Varying Sizes

Up until now, experiments on two transmission routes have been considered, namely droplet nuclei and droplets (sections 4.1 and 4.2), and they correspond to two infection routes: droplet infection and airborne infection.

CFD simulations can also be used for the prediction of the transport of droplet nuclei or of large droplets by for example an Eulerian specification of the flow field, see Bjørn and Nielsen (2002) and Gao and Niu (2007). Liu (2011) has developed a CFD model with a Lagrangian specification of the flow field where a transition can take place from droplet-borne infection to airborne infection, because the exhaled droplets can evaporate in the air and transform the droplets to droplet nuclei, depending on the humidity in the surroundings of the exhalation flow.

Figure 11. *The left figure shows the exhalation of 100 µm droplets in 35 % RH and the right side shows the same exhalation in surrounding air with a 95 % RH after 12 sec of exhalation.*

Figure 11 shows the influence of the humidity on water-contained droplets which may contain viruses or bakeries. The left side of the figure shows the flow and evaporation in surroundings with humidity of 35 %. The particles decrease in size (~ 60 µm) and move upward within the thermal boundary layer flow from the two persons. The target person (grey) will be directly influenced by the exhaled particles. The situation is different in the case where the surrounding air has a humidity of 95 %. The exhaled and water containing particles from the source manikin (red) will not decrease much in diameter (~ 90 µm) and they fall down to the floor due to gravity.

5 Conclusions

Full-scale experiments with tracer gas can be used to simulate the movement of droplet nuclei in the air in ventilated rooms. The concentration distribution of tracer gas gives an estimate of the airborne cross-infection risk in a room.

A high flow rate in a room is possible with mixing ventilation and vertical ventilation. The highest flow rates can be achieved without causing draught in the room when the supply system has a large supply area, as for example a large number of ceiling-mounted diffusers.

The air distribution system suggested by CDC for isolation rooms fulfils the requirement for a high flow rate, but the flow will be fully mixed without the reduced cross-infection effect of unidirectional flow.

A high ventilation index can reduce the cross-infection effect, but it is difficult to obtain in practice if it is based on a thermal force, because this may gradually disappear at high flow rates.

Displacement ventilation has a high ventilation index, but it is also possible to have stratified exhalations in the occupied zone because of the vertical temperature gradient. This effect may increase the cross-infection, and the system cannot be recommended.

Personalized ventilation built into a hospital bed is a new interesting possibility which can be used to reduce the cross-infection problem without making separate rooms for each patient.

Transmission of exhaled gaseous substances from one person to another in an indoor environment takes place both in a direct way and via the room air distribution.

The distance between people, positions of people as face-to-face, face-to-side of the target person, face-to-back of the target person, and a seated source person, have been studied. The studies show that the exposure increases with a decreasing distance between people, and the highest values are obtained in the face-to-face position. This is a serious setback for the displacement ventilation system with respect to the protection against cross-infection. Face-to-side is also giving some

exposure to a person, while facing a person's back does not give any direct exposure via the microenvironment. The thermal stratification and the rising flow of the exhalation in the room support a significant exposure of a standing person when the source person is seated breathing towards the chest of a standing target person.

It is indicated that people of different heights could be more or less exposed than found in the measurements.

Experiments with test particles show that large droplets reach the floor within 1 m from the person breathing in a horizontal direction. There is a similarity between the characteristics of the infection risk by airborne transmission and by droplet-spread transmission, which could make it difficult to distinguish the two different principles of cross-infection risk.

Finally, studies show that a CFD method can be used for the simulation of water containing droplets including the transformation from droplets to droplet nuclei. This transformation is influenced by the humidity in the surroundings of the source person.

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