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Experimental Measurements of Particles and CO_2 Exhaled by a Manikin in a Hospital Room

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ABSTRACT

The relation between the concentration and particle size of the human breathing and the way in which these particles are dispersed in hospital indoor environments are studied in this research.

Breathing thermal manikins are used to, experimentally, simulate a human person and its breathing activity. Two breathing thermal manikins are placed in a hospital room, simulating an infected patient, together with another standing manikin simulating a health worker. 0.665 and 1.095 µm sized particles and CO_2 tracer gas are injected in the exhalation of the patient manikin simulating exhaled contaminants.

The results show that the breathing function of patient manikin (exhaling through the mouth or through the nose) influence the personal exposure to contaminants at certain distance from the contaminants source for the largest particles (1.095µm). The microenvironment generated by the two BTM and the direction of the exhalation flow have a significant influence in the dispersion and exposure of the exhaled contaminants. It is shown that the dispersion of the exhaled particles (0.665µm) and the CO2 is similar in the two positions measured. However, the largest particles (1.095 µm) show significant differences at certain distance from the exhalation source.

The results show the pros and cons of each measurement strategy (particles and tracer gas) in order to obtain, from an experimentally point of view, an accurate prediction of a personal exposure index between people in a hospital room.

INTRODUCTION

Hospital environments are critical environments for cross-infections due to close interaction between healthy and infected people. Ventilation in hospital environments is used to provide occupants with clean air for breathing and intended to create safe environments. Mixing and displacement ventilation strategies plays an important role in the exposure to exhaled contaminants in hospital settings (Berlanga et al. 2017; Berlanga et al. 2018a; Berlanga et al. 2018b). The effect of airflow distribution on personal exposure to indoor air contaminants has been shown in previous studies (Olmedo et al. 2012; Rim et al. 2009; Zhao et al. 2004). Computational fluid dynamics, CFD, and full-scale experimental tests are used to study temporal and spatial distribution of exhaled contaminants. The influence of the breathing function in the dispersion of exhaled contaminants has been found en CFD previous studies (Villafruela et al. 2016). Breathing thermal manikins, BTM, are used in full-scale experimental tests to investigate the dispersion and exposure to exhaled contaminants. Breathing mode should be considered as an important factor as the risk of cross-infection is influenced by the pulmonary ventilation rate and breathing cycle period (Ai et al. 2019).
Tracer gases, such as N_2O and CO_2, are usually accepted as a surrogate of airborne particles smaller than 5-10 µm in many research works (Tang et al. 2011). Recent studies have compared tracer gas and aerosol particles distribution indoors

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and the impact of ventilation rate and interaction of airflows (Bivolarova 2017) as well as other factors affecting spatial and temporal distribution (Belut 2019). However, control of airborne contaminants in buildings should be further investigated (Mesquita et al. 2021).

The objective of this study is to investigate the dispersion of exhaled contaminants in the air. Experiments are conducted in a test room using two BTM to simulate a lying patient (P) and a standing health worker (HW). The use of CO_2 tracer gas as a surrogate of two different particle size is investigated under a mixing ventilation strategy and a fixed air change per hour, ACH. Personal exposure index is used in each case to evaluate the contaminant concentration in the near environment of a patient to indoor exhaled contaminants using two breathing modes through nose or mouth.

METHODOLOGY

Laboratory set-up

The experimental study was carried out in a controlled environmental chamber at the University of Cordoba. The chamber simulates a hospital room sized 4.5 m (14.76 ft) length, 3.3 m (10.83 ft) width and 2.8 m (9.19 ft) height. Two BTM are place in the room as can be seen in Figure 1. Clean air is supplied to the chamber through two 400x140 mm (1.31x0.46 ft) wall grilles (AEH, Trox, Germany) placed on the upper part of one of the walls, G. The air is exhausted through two 800x140 mm (1.31x0.46 ft) wall grilles (AEH, Trox, Germany), E, placed on the upper part of the opposite wall, close to the manikins, as shown in figure 1. The ventilation system was set at 62.5 m^3/h (1.5 ACH) supplying HEPA (H14) filtered clean air at a supply temperature of 17 ºC to maintain a mean air temperature in the chamber of 24 ºC.

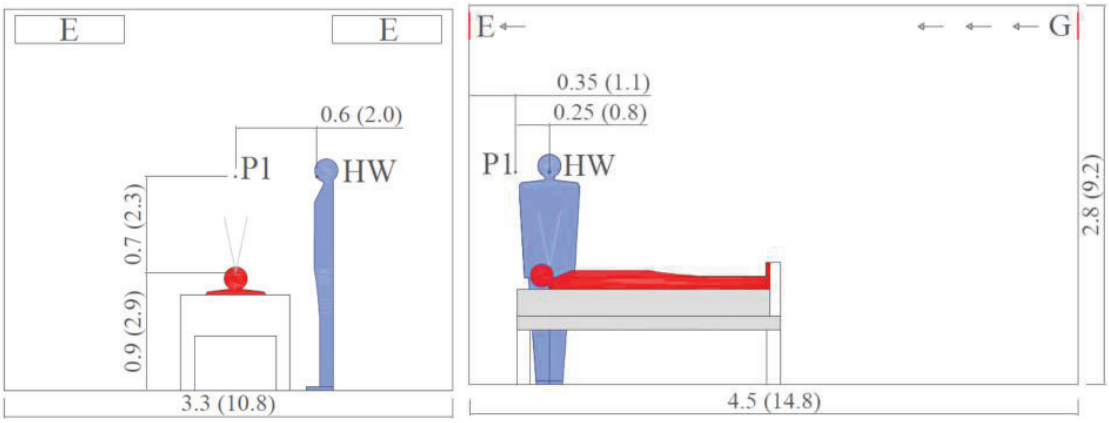

Figure 1. Set-up of the experimental room with the two BTM, a patient (P) lying in a bed (red) and a health worker (HW) standing near the bed (blue). The measuring points of concentration of contaminants: P1, E and inhalation of HW (a) Front view (b) Side view of the room. Measurements in m (ft).

Two BTM with a mean surface temperature of 34ºC were placed in the experimental room. One of the manikins represents a patient, P, lying in bed, and the other a health worker (HW) standing 0.2 m (0.66 ft) from the bed side. The HW manikin breathes inhaling and exhaling through the mouth while the P manikin breathing function was set through the mouth or through the nose depending on the case. Each manikkin generates sensible heat gain, 80 W (272.97 btu/h) for HW and 70 W (238.85 btu/h) for P manikin, which correspond to a man of 70 kg (154.32 lb) weight and 1.7 m (5.58 ft) height.

The breathing function was configured based on the research carried out by Gupta (Gupta 2010). A breathing cycle of 0.55 l (0.02 ft^3) of tidal volume, a respiration frequency 17.90 min^{-1} of inhalation and 16.43 min^{-1} of exhalation and a minute volume of 9.46 l /min (0.05 ft^3/hr) was used for both BTM. The P manikin is considered a source of contaminants and HW manikin is considered an exposed person. Particles sized 0.665 and 1.095 µm (aerodynamic diameter), and CO_2 tracer gas are injected in the exhalation of P manikin to simulate emission of contaminants during a normal breathing. Tests are carried out once stationary temperature conditions are obtained inside the experimental room. Figure 2 shows a real picture of the experimental set-up.

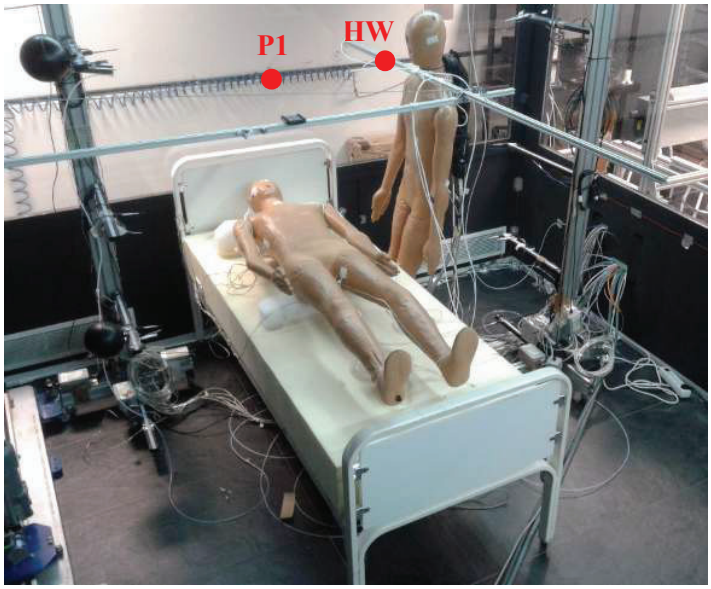

Figure 2. Picture of the experimental chamber with the two BTM: HW standing to the right and P manikin lying on a bed. The measuring points are represented by P1 and HW.

Table 1 show two cases studies carried out. The first one using the exhalation of P manikin through the mouth and the second case using the exhalation through the nose. In both cases, particles and CO_2 were inyected in the exhalation air.

Table 1. Experimental case studies.

Case study	Breathing in P manikin	ACH	Particle size [µm]	Tracer gas (ppm)
1	Mouth	1.5	0.665 1.095	CO_2
2	Nose		0.665 1.095	

Stationary particles and CO_2 concentrations were reached after 3 hours. Final 15 minutes of stationary particles and CO_2 concentrations were selected to calculate the contaminants exposure indices.

Instrumentation

A monodisperse aerosol generator (CMAG 3475, TSI) was used to generate particles using Di-Ethyl-Hexyl-Sebacat (DEHS). CO_2 tracer gas were dosed with a Innova 1403 device (LumaSense Technologies, California). Before each experimental test, particles and CO_2 concentrations inside the experimental chamber were cleaned by using ventilation system equipped with HEPA (H14) air filters and renovating completely the air inside the chamber.

The particle concentration was measured with an aerodynamic particle device (Aerodynamic Particle Sizer 3321, TSI) and an optical particle device (Optical Particle Sizer 3330, TSI) at three points in the room: P1, HW and E, see figure 1. Both particle measurement devices presented an uncertainly of 5% and were configured to log data every second. The CO2 tracer gas concentration was measured with a multipoint sampler and doser (Innova 1403, LumaSense Technologies, California) and a photoacoustic field gas monitor (Innova 1512, LumaSense Technologies, California) at the same measuring points P1, HW and E, and also at the supply grille, G. Both devices presented an uncertainly of 2% and were configured to log data every 35 seconds.

Evaluation indexes

To evaluate the exposure to exhaled contaminants the personal exposure index is measured at location P1 (0.7 m above P manikin´s exhalation) and HW location (1 cm in front the HW manikin´s mouth). That index using particules measurements is described by the following equation:

$$\varepsilon = c_{inh}/c_R \quad (1)$$

where c_{inh} is the average concentration of particles measured at P1 and HW points, and c_R is the average concentration of particles in the air exhaust grilles of the room (E).

For the CO_2 measurements the personal exposure index must consider the CO_2 present in the clean air entering the room (c_s). The definition of the index is the same as before, but using the increment in CO_2 concentration at P1 and HW points respect to the CO_2 concentration in the supply air. The index is described as follows:

$$\varepsilon = (c_{inh}-c_s)/(c_R-c_s) \quad (2)$$

A personal exposure index equal to 1 is obtained under perfect mixing ventilation design. Values of personal exposure index greater than 1 show a poor dilution of the contaminants in the near environment, P1 and HW points, while personal exposure index lower than 1 show an important dilution of the contaminants in the considered measurement points.

EXPERIMENTAL RESULTS

The average personal exposure, ε, is obtained measuring particles and CO_2 concentration for 15 minutes at two locations, P1 and HW. The results obtained when P manikin is exhaling through the mouth are shown in Figure 3.

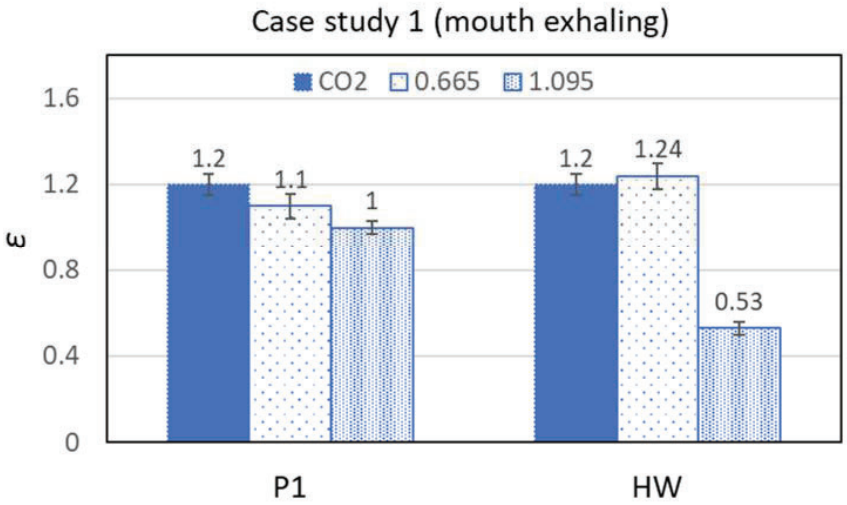

Figure 3. Average personal exposure (ε) measured at two locations in the room: P1 and HW when P manikin is exhaling through the mouth.

The values of ε using CO_2, 0.665 and 1.095 µm particles are similar in the position P1. Values between 1 and 1.2, corresponding to a mixing airflow strategy were found in P1 position. However, the results differ at the HW point, just in front the HW manikin, where an average personal exposure of 0.53 was found for 1.095 µm particles. This reduction in the exposure index may be due to the higher deposition of this particles at larger distances from the exhalation point, especially because this point is out of the exhalation jet direction. The exposure obtained with CO_2 and 0.665 µm particles at HW are very similar and close to 1.2 indicating a relative poor mixing process.

Figure 4 shows the same results when the P manikin exhales through the nose. As it was observed before, ε at P1 position is very similar when it is obtained using CO_2 or particles (0.665µm and 1.095µm). However, again the larger particles (1.095µm) shows a different behaviour at longer distance from the source, at the HW position.

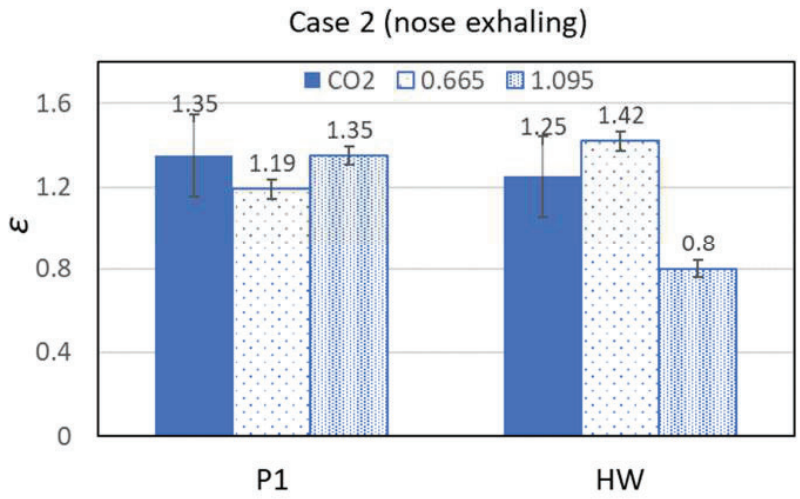

Figure 4. Average personal exposure (ε) measured at two locations in the room: P1 and HW when P manikin is exhaling through the nose.

The values of exposure for mouth exhaling, case 1, and nose exhaling, case 2, in P1 are similar but higher in the case 2. This may be due to the direction of the exhalation jet. While for mouth exhaling, case 1, the exhalation is conducted directly to the exhaust grilles placed very close to the P manikin, for nose exhaling, case 2, the exhalation is conducted in the opposite direction which may make more difficult for the clean air drive the exhaled contaminants to the exhaust grille, E.

The behaviour of the largest particles (1.095µm) differs from the CO_2 and tiny particles (0.665µm) for HW, placed at longer distance from P manikin exhalation, than P1 point. This fact may be caused by the greater deposition of these particles and the effect of the thermal plume of the HW manikin that helps the tiny particles and CO_2 to go upward while the largest particles are deposited.

The direction of the contaminated exhalation flow (mouth) to the upper part of the room, case 1, where the exhaust grilles E are placed, reduces the dispersion of contaminants in the room showing a lower concentration of contaminants in the two meauring points. However, exhalation by the nose, case 2, shows values of personal exposure higher in all the points. The exhalation flow in the opposite direction to the exhaust grille, E, produces a higher dispersion of contaminants and, therefore, a higher exposure to contaminants in P and HW measurement points.

Study limitations

DEHS particles used to simulate the contaminats have a different composition of those generated by a human lung. This fact may lead to different results in the deposition and evaporation process of these particles and therefore their dispersion behaviour. The number of exhaled particles are not equivalent to that exhaled by a human being. The risk of infection is not being evaluated, only the exposure generated by certain number of particles at different positions in an indoor environment.

CONCLUSIONS

The experimental tests carried out increase the knowledge about the dispersion of exhaled contaminants simulated by particles of different sizes and CO2 as a tracer gas. It can be said that the dispersion of the tiny particles (0.665µm) and the CO2 is similar in the two positions measured. However, the largest particles show significant differences at certain distance from the exhalation source.

The breathing function of P manikin (exhaling through the mouth or through the nose) influence the personal exposure to contaminants at certain distance from the contaminants source for the largest particles (1.095µm). The microenvironment generated by the two BTM and the direction of the exhalation flow have a significant influence in the dispersion and exposure of the exhaled contaminants.

Further studies must be carried out to obtain more information about exhaled particle simulation. The use of more measuring points may increase the knowledge on the dispersion for particles of different sizes.

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NOMENCLATURE

ACH	=	Air change per hour (h^{-1})
BTM	=	Breathing thermal manikin
CFD	=	Computational fluid dynamics
c_{inh}	=	Inhaled air contaminant concentration (particles/cm^3) and (ppm)
CO_2	=	Carbon dioxide, as a tracer gas
c_R	=	Exhaust air contaminant concentration (particles/cm^3) and (ppm)
c_s	=	Supply air contaminant concentration (particles/cm^3) and (ppm)
DEHS	=	Di-ethyl-hexyl-sebacat
E	=	Exhaust grilles
G	=	Supply grilles
HW	=	Health worker
P	=	Patient
P1	=	Measuring point
ε	=	Personal exposure index

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