Influence of a portable air cleaner location on the exposure to exhaled contaminants in hospital rooms

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Abstract. Indoor environments with a deficient mechanical ventilation, could increase exposure to exhaled contaminants. This situation is critical in hospital environments such as hospital rooms. In this situation, a portable air cleaner system based on high efficiency air filters maybe a solution by itself or combined with mechanical ventilation systems to reduce the concentration of aerosols in hospital room environments.

In this study the influence of the location of a portable air cleaner based on high efficiency air filters on the exposure to exhaled contaminants of a health worker close to a patient lying on a bed was investigated.

The experimental setup consists of a hospital room (40.84 m³) with two breathing thermal manikins, BTM. One BTM was lying on the bed (patient) and the other BTM was stand up near the bed (health worker). Each BTM has its own independent breathing system with the capability of performing different breathing flows. Both BTM inhale and exhale through the mouth with a respiration frequency of 17.90 min-1 (inhalation) and 16.43 min-1 (exhalation). Both has minute volume 9.46 (l/min) and tidal volume 0.55 l. The BTM lying on a bed, simulated the source of exhaled contaminants and exhales particles sized 0.57-0.76 µm.

A total air flow rate of 150 m³/h (3.67 ACH) was used in all experimental tests. The total air flow rate was generated only by the air cleaner, only by the ventilation system or using a combination of the air cleaner and the ventilation system. The concentration of particles was measured in the inhalation of the standing BTM close to bed, and in other points of the room to analyse the influence of air cleaner location on the exposure to airborne contaminants.

The results suggest that the air diffusion plays an important role in the exposure to exhaled contaminants in a hospital room. In these indoor environments, low values in the exposure to exhaled contaminants can be obtained using a combination of a portable air cleaner located near the source of contaminants and the ventilation system or using only 100% air flow rate in the ventilation system.

Keywords. Air cleaner, exhaled contaminants, airborne contaminants exposure, hospital rooms
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1. Introduction

The patients in hospital rooms exhale particles when they speak, cough or sneeze. In hospital rooms there are infected patients and healthy people as worker or family members which are interacting continuously with each order therefore it is necessary to create safe hospital environments through different ventilation strategies.

Ventilation in hospital rooms is necessary to create a safe environment. Clean air can be supply in the room through a ventilation mechanic system or ventilation natural. Some authors have been developed previous studies about ventilation in hospital rooms. The effect of different ventilation systems on particles in a hospital room [1]. Influences of ventilation on the exposition to particles generated by patient and medical staff [2]. This study indicates that localized ventilation can be a solution to combine to ventilation system to reduce cross infection risks between patient and medical staff. Separate and combined effects of ventilation rate, airflows interaction of manikin on the distribution of particles in a single-bed hospital room [3]. Use of four different mixing ventilation configurations in hospital rooms based on ventilation performance and health workers exposure to the contaminants released by an infected patient [4][14].

There are situations where a hospital room has a poor ventilation. A solution to control the exposure of particles may be the use of portable air cleaners. A portable air cleaner control and reduce the exposure of particles. A portable air HEPA cleaner assist to reduce the risk of exposure of particles. Portable air cleaner increases the effective clean airflow rate in the hospital rooms. The influence of the portable HEPA air cleaner on the airflow was studied through of Computational Fluid Dynamics, CFD, simulations [5]. Recent studies evaluate the efficiency of portable air cleaner based on Clean Air Delivery Rate, CADR [6][7] and different positions inside the room [6][7][8][9].

The combination of a ventilation system and a portable air cleaner has been studied by several authors. In [5] raises that a portable air HEPA cleaner increase the effective airflow rate of the hospital room. The study [8] indicates that combination between two portable air HEPA cleaners and ventilation system reduced overall exposure by up to 90%. The portable air HEPA cleaners were most effective when they were close to aerosol source.

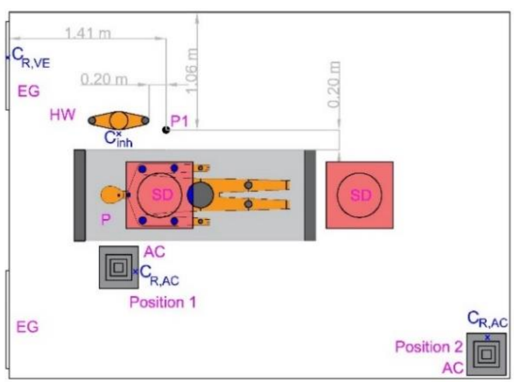
The objective of this study was to investigate the exposure of particles in a hospital room under different ventilation strategies: only a portable air cleaner active, only a ventilation system active or a combination of both systems. Influence of the position of the air cleaner in the room was also investigated. Experimental tests were carried out in an experimental chamber that simulate a hospital room where two breathing thermal manikins, BTM, were used to simulate a lying infected patient and a standing exposed healthy worker.

2. Methodology

2.1 Setup

The experimental study was carried out in a controlled environmental chamber at the Universidad de Cordoba [4][14].

(a)



(b)

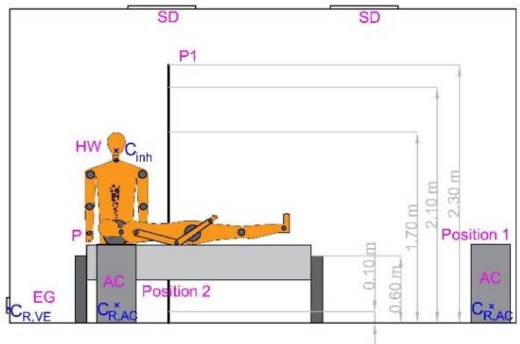


Fig. 1 – Experimental setup (a) Layout view (b) Side view.

The experimental chamber simulates a hospital room. The dimensions of the chamber are length 4.5 m, width 3.3 m and height 2.8 m. Inside the chamber, there were two breathing thermal manikins, three particles measurement equipment, a portable air cleaner and a temperature pole. The experimental setup is shown in Fig.1.

2.2 Breathing thermal manikins

Two breathing thermal manikins, BTM, [4][14] with a surface temperature of 34ºC were placed in the room. One of the manikins represented a patient, P, lying in bed, and the other represented a health worker (HW) standing 0.2 m from the bed side. Both manikins breathed through their mouth or their nose. The P and HW manikins generated a heat gain of 70 W and 80 W respectively, which correspond to a man of 70 kg weight and 1.7 m height. The breathing function was configured based on the research carried out by Gupta [16]. A breathing cycle of 0.55 l 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 was used for both breathing thermal manikins.

Particles were injected in the breathing air to simulate emission of contaminants through the exhaled air in the P manikin. P manikin is considered source manikin and HW manikin is considered as an exposed person. A portable test aerosol generator (3073, TSI) was used to generate particles. Di-Ethyl-Hexyl-Sebacat (DEHS) was used to generate particles in the generator. The average exhaled concentration, C_0, was measured, in the P manikin exhalation. The average exhaled concentration, C_0, was 12647 #/cm^3 in the experimental tests.

2.3 Experimental conditions

Clean air is supplied to the chamber through two 400x16 mm swirl diffuser, SD, (VDW, Trox, Germany) placed on the ceiling of the chamber. The air is exhausted through two 400x140 mm wall grilles, EG, (AEH, Trox, Germany) placed on the lower part of the wall. At the same time a portable air cleaner, AC (Pure Airbox Home, Zoneair 3D), was used to supply clean air to the chamber through a 280x280 mm square diffuser (DLQ, Trox, Germany).

Before each experimental test, the ventilation HEPA H14 filtered air was supplied to the experimental chamber until the concentration of particle was reduced to a minimum value. Experimental tests were carried out once stationary air temperature conditions, 22ºC, were obtained inside the chamber. Experimental ambient conditions were considered stationary when the variation in the air temperature inside the experimental chamber remain under 0.5ºC.

2.4 Measurement equipment

Five temperature sensors were placed in a pole P1 at different heights, see fig. 1. Each temperature sensor consists of a J-type thermocouple with an accuracy of 2% in the range 15ºC to 45ºC.

Particle concentration measurements were carried out in three points in the experimental chamber. One particle measurement point was placed near of BTM mouth, see C_{inh} in fig. 1. A particle measurement point was placed in the exhaust wall grill, see $C_{R,VE}$. A last particle measurement point was placed in the exhaust AC, see $C_{R,AC}$. The particle concentration in the range of 0.57 to 0.76 µm, was measured every second with three optical particle device (Optical Particle Sizer 3330, TSI), OPS. The OPS measurement equipment has an uncertainly of 5%.

2.5 Case studies

Seven experimental tests were carried out using only the ventilation system, only the portable air cleaner or using a combination of both systems. In each case, the total air flow was set to 150 m^3/h (3.67 ACH) see table 1. The total airflow was distributed between the ventilation system and the air cleaner using different percentages in each case study. Case study 1 correspond to 100% air flow rate using only the portable air cleaner. A 100% air flow rate was used in the ventilation system in the case study 4. A distribution of 60% of the total air flow for air cleaner and 40% for the ventilation system, was used in case study 2, or vice versa, in the case study 3. Moreover, in each case study two locations of the air cleaner in the chamber were used, near of bed, N, and faraway of bed, F, see figure 1. As a result, seven experimental tests were performed, see table 1.

Tab. 1 – Experimental test carried out.

Case study	Experimental Test	ACH (h^{-1})	
		Ventilation system	Portable air cleaner
1	1F 1N	0	3.67
2	2F 2N	1.47	2.20
3	3F 3N	2.20	1.47
4	4	3.67	0

3 hours experimental tests were performed to ensure that the particles concentration in the measurement points was stationary. 15 minutes of stationary concentration measurements were selected at the end of each experimental test to calculate the contaminants exposure indices.

2.6 Contaminants exposure indices

To evaluate the exposure to exhaled contaminants in a hospital room setup, two contaminants exposure indices were used: a modified personal exposure index and the intake fraction index.

The personal exposure, ε, [11][12][13][14][15], is defined as the ratio between the average concentration of contaminants in the inhalation of an exposed person, such as HW manikin, and the average concentration of contaminants in the exhaust of the ventilation system:

$$\varepsilon = \frac{\int_0^t \dot{Q}_{inh} \cdot C_{inh}}{\int_0^t \dot{Q}_{R,VE} \cdot C_{R,VE}} \qquad (1)$$

Different experimental tests were performed with the combination of a portable air cleaner and a ventilation system in this study. So, two different exhaust systems were active simultaneously: the exhaust of the portable air cleaner and the exhaust of the ventilation system. Thus, a modified personal exposure index, ε_c, was used in this study to evaluate the personal exposure in the exposed person, manikin HW:

$$\varepsilon_c = \frac{\int_0^t \dot{Q}_{inh} \cdot C_{inh}}{\int_0^t \dot{Q}_{R,AC} \cdot C_{R,AC} + \int_0^t \dot{Q}_{R,VE} \cdot C_{R,VE}} \quad (2)$$

where C_{inh}, is the average concentration of particles measured in the inhalation of HW manikin, $\dot{Q}_{inh}$, is the inhalation air flow rate of HW manikin, $C_{R,AC}$, is the average concentration of particles measured in the exhaust of portable air cleaner, $\dot{Q}_{R,AC}$, is the air flow rate in the exhaust of portable air cleaner, $C_{R,VE}$, is the average concentration of particles measured in the exhaust of ventilation system, $\dot{Q}_{R,VE}$, is the air flow rate in the exhaust of the ventilation system and, t, is the time.

The intake fraction, IF, defines the proportion of particles that an exposed person inhales, HW manikin, referred to the particles exhaled by a source person, P manikin [11], which can be expressed as:

$$IF = \frac{\int_0^t \dot{Q}_{inh} \cdot C_{inh}}{\int_0^t \dot{Q}_0 \cdot C_0} x100 \quad (3)$$

where C_0 is the average concentration of particles exhaled by P manikin and $\dot{Q}_0$, is the air flow rate exhaled by the P manikin. The concentration of particles in the mouth section of P manikin, C_0, was carefully measured at the beginning of each experimental test.

2.7 Clean Air Delivery Rate

The performance of the ventilation system, the air cleaner and the combination of both systems was evaluated using the Clean Air Delivery Rate, CADR [10]. After each experimental test, the injection of particles was inactivated, whereas the portable air cleaner and/or the ventilation system were maintained active to obtain the CADR using the decay method for each experimental test.

The decay constant k_n and decay natural constant k_s in the experimental chamber were obtained using the equation:

$$C_{(t)} = C_i e^{-kt} \quad (4)$$

where $C_{(t)}$ is the concentration measure at the instant t, C_i is the concentration measure at the instant $t = 0$, t is the time, k_n is the decay constant for each test and k_s is the natural decay constant of the experimental chamber.

Then, the CADR was calculated as:

$$CADR = V(k_n - k_s) \quad (5)$$

where V is the volume of the experimental chamber.

3. Results

3.1 Temperature conditions

The experimental tests were carried out with an average air temperature of 22 ºC inside the experimental chamber.

3.2 Modified personal exposure index

Average values of the modified personal exposure index, ε_c, are represented in fig. 2 for different experimental tests. All the experimental results were carried out using a total airflow rate of 150 m^3/h (3.67 ACH).

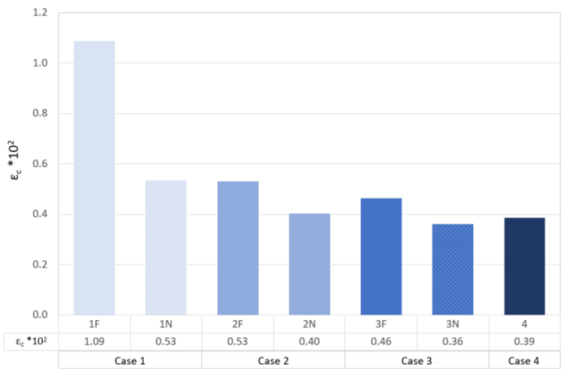


Fig. 2 – Experimental results of modified personal exposure index, ε_c.

The higher value, 1.09 10^{-2}, of modified personal exposure index, ε_c, was found using only the air cleaner in the position far away from the bed with an air flow rate of 3.67 ACH, see experimental test 1F in fig. 2.

However, if the air cleaner is located near the bed using the same air flow rate of 3.67 ACH, experimental test 1N in fig. 2, the modified personal exposure index, ε_c, is reduced from 1.09 10^{-2} to 0.53 10^{-2}. The same value, 0.53 10^{-2}, of the modified personal exposure index, ε_c, was found using the same air flow rate of 3.67 ACH but with a distribution of 60% of the total air flow for air cleaner and 40%for the ventilation system, see experimental test 2F in fig. 2.

Lower values in the modified personal exposure index, ε_c, were found using the same air flow rate of 3.67 ACH but with a distribution of 60% of the total air flow for air cleaner and 40% for the ventilation system, see case study 2 in fig. 2. In this case, values of 0.53 10^{-2} and 0.40 10^{-2} of modified personal exposure index, ε_c, were found locating the air cleaner far away from the bed, experimental test 2F, and near the bed, experimental test 2N, respectively. Similar value, 0.39 10^{-2}, of the modified personal exposure index, ε_c, was found using only the ventilation system, see experimental test 4 in fig. 2.

These experimental results in the modified personal exposure index, ε_c, are very close to those obtained with a distribution of 40% of the total air flow for air cleaner and 60% for the ventilation system, see case study 3 in fig. 2. In this situation, values of 0.46 10^{-2} and 0.36 10^{-2} of modified personal exposure index, ε_c, were found locating the air cleaner far away from the bed, experimental test 3F, and near the bed, experimental test 3N, respectively.

These results suggest that it is possible to obtain low values in the modified personal exposure index, ε_c, if the air cleaner is located near source of contaminants, manikin P or if a 100% air flow rate is used in the ventilation system. These reduced values of exposure are obtained if the air cleaner or ventilation system are used alone or if the air cleaner is used in combination with the ventilation system using different percentages of distribution of the total air flow rate.

3.3 Intake fraction

Average values of the intake fraction index are represented in fig. 3. All the experimental results were carried out with an airflow rate of 150 m^3/h (3.67 ACH).

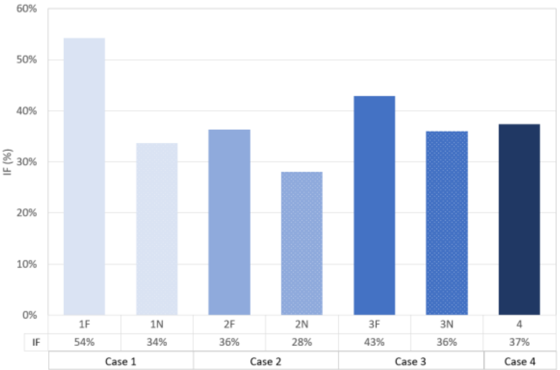


Fig. 3– Experimental results of intake fraction index, IF.

The higher value of intake fraction, 54% is obtained when the air flow rate is generated only by the air cleaner and it is located far away from the bed, see experimental test 1F in fig. 3. However, the IF can be reduced to 34% if the air cleaner is located near the bed using the same air flow rate. So, the closer the air cleaner is located to the source of contaminants, P manikin, the lower is the IF in the HW manikin.

Higher values of IF values were found when a distribution of 40% of the total air flow for air cleaner and 60% for the ventilation system, see case study 3 in fig. 3, than those with a distribution of 60% of the total air flow for air cleaner and 40% for the ventilation system, see case study 2 in fig. 3. In these case studies, IF values of 43% and 36% were found when the air cleaner is located far away from the bed and IF values of 36% and 28% were found when the air cleaner is located near the bed. Again, a reduction of IF can be found in both case studies if the air cleaner is located near the source of contaminants, P manikin.

Similar values of IF, 37%, was found using only the ventilation system, as shown in fig. 3. Slightly lower values in IF were found using a combination of the ventilation system and the air cleaner when the air cleaner is located near the bed, 28%, 34% and 36% for the experimental tests 2N, 1N and 3N respectively.

3.4 Normalized decay curve and Clean Air Delivery Rate

Normalized decay curves are represented in fig.4. All the experimental tests were carried out using an airflow rate of 150 m^3/h (3.67 ACH).

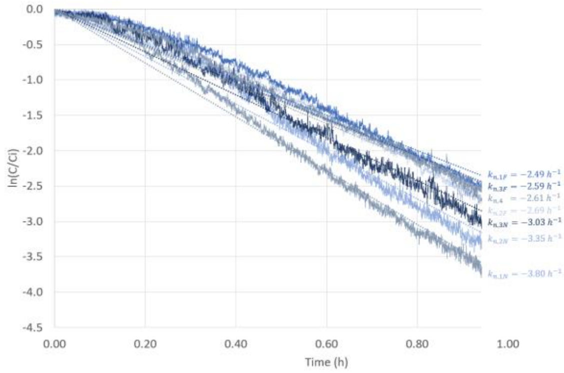


Fig. 4 – Experimental results of normalized decay curve.

Experimental tests 1F, 3F, 4 and 2F show a slope of the normalized decay curve lower than rest of tests, with a decay constant k_n of -2.49, -2.59, -2.61 and -2.69 h^{-1} respectively, as shown in fig. 4.

The higher slope in normalized decay curve is obtained in experimental tests 3N, 2N and 1N, with a decay constant k_n of -3.03, -3.35 and -3.80 h^{-1} respectively, as can be seen in fig. 5. These results show that if the air cleaner is located near the source of contaminants, P manikin, it can be obtained a faster reduction of contaminants in HW manikin.

A natural decay constant, k_s, of the experimental chamber of -0.15 was determined in different experimental tests.

Clean Air Delivery Rate was calculated using equation 5. CADR results are represented in fig. 5 for all the experimental tests. All the experimental results correspond to an airflow rate of 150 m^3/h (3.67 ACH).

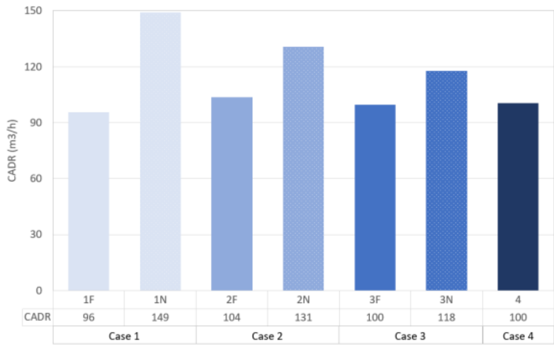


Fig. 5– Experimental results of CADR.

Fig. 5 show that if the portable air cleaner is placed far away of bed, experimental tests 1F, 2F, 3F or there is only ventilation system active, experimental test 4, the CADR values are similar, 96, 104, 100 and 100 m^3/h respectively.

If the portable air cleaner is placed near of bed the CADR values are higher compared to the rest of the tests, experimental tests 1N, 2N and 3N, see fig. 5, showing values of 149, 131 and 118 m^3/h respectively.

These results suggest that a reduction on exposure to airborne contaminants can be obtained using only the air cleaner, experimental test 1N, or a combination of the air cleaner and the ventilation system, experimental tests 2N and 3N. Higher values of CADR are found in these situations if the air cleaner is near the source of contaminants, manikin P.

4. Study limitations

In this study a set of experimental tests is performed in a hospital room setup using three different particle concentration measurements equipment. A more detailed study could be performed if there were available more particle concentration measurement points. Moreover, the effect of different air flow rates and other combination of the air cleaner and the ventilation systems should be investigated. Exhaled contaminants behaviour can differ of that observed using DEHS particles in this study. Convective air flows could be different if the considered heat gains in the hospital room were changed. In these situations, the results of this study should be completed.

5. Conclusions

The exposure to exhaled contaminants in a hospital room under different ventilation strategies using a portable air cleaner active in combination with a ventilation system has been carried out in an experimental chamber using two breathing thermal manikins. Different experimental tests were carried out using a total air flow rate of 150 m^3/h (3.67 ACH).

Based on the results obtained, the following conclusions can be drawn:

- Low values in the exposure indices can be obtained if the air cleaner is located near the source of contaminants in a hospital room environment or if it is used only the ventilation system. In these cases, high CADR values were obtained, using only the air cleaner, 149 m^3/h or a combination of the air cleaner and the ventilation system 131 and 118 m^3/h respectively.

- If it is used only the air cleaner and it is located far away the source of contaminants in a hospital room environment, a low value in the CADR, 96 m^3/h, and high values of modified exposure index, 1.09 10^{-2}, and intake fraction index, 54%, were obtained.

- A significant reduction in the modified exposure index, 1.09 10^{-2} to 0.53 10^{-2}, and in the intake fraction index, 54% to 34% were found when it is used only the air cleaner and it is changed from a far location to a near location to the source of contaminants, in manikin P.

- Similar results in exposure indices were found with a distribution of 60% of the total air flow for air cleaner located far away the contaminant source and 40% for the ventilation system, a distribution of 40% of the total air flow for air cleaner located far away the contaminant source and 60% for the ventilation system, or a 100% air flow rate in the ventilation system. In these cases, were obtained values of the modified exposure index, 0.53 10^{-2}, 0.46 10^{-2} and 0.39 10^{-2} respectively, the intake fraction index, 36%, 43% and 37% respectively, and the CADR, 104, 100 and 100 m^3/h respectively.

These results suggest that low values in the exposure to exhaled contaminants can be obtained using a combination of a portable air cleaner located near the source of contaminants and the ventilation system or using only the ventilation system. Both the air diffusion and the incomplete air mixing play an important role in the exposure to exhaled contaminants in a hospital room environment.

Further studies should be carried out to completely investigate the influence of these issues in the exposure to exhaled contaminants in hospital room environments using a combination of a portable air cleaner and a ventilation system.

The datasets generated during and/or analysed during the current study are available in the ZENODO repository, 10.5281/zenodo.6334442.

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