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Experimental and Numerical Analysis of the Relationship between Indoor and Outdoor Airborne Particles in an Operating Room

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Operating room, ventilation, filtration, balance mass model, airborne particles, outdoor air.

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Abstract

This work investigated the impact of the HVAC filtration system and indoor particle sources on the relationship between indoor and outdoor airborne particle size and concentrations in an operating room. Filters with efficiency between 65% and 99.97% were used in the investigation and indoor and outdoor particle size and concentrations were measured. A balance mass model was used for the simulation of the impact of the surgical team, deposition rate, HVAC exhaust and air change rates on indoor particle concentration. The experimental results showed that high efficiency filters would not be expected to decrease the risk associated with indoor particles larger than approximately 1 µm in size because normal filters are relatively efficient for these large particles. A good fraction of outdoor particles were removed by deposition on the HVAC system surfaces and this deposition increased with particle size. For particles of 0.3-0.5 µm in diameter, particle reduction was about 23%, while for particles >10 µm the loss was about 78%. The modelling results showed that depending on the type of filter used, the surgical team generated between 93-99% of total particles, while the outdoor air contributed only 1-6%.

Introduction

Knowledge of the variation in indoor particle concentrations in operating rooms, as well as the factors which affect these variations, are very important in order to help control the incidence of surgical site infections.

Indoor particles in an operating room, can be easily dispersed by draughts and can remain in suspension for several hours, before being deposited on indoor surfaces (floor, walls and equipment), due to the effect of gravity. Any movement of air close to indoor surfaces can also cause re-suspension of these particles. Similarly, microorganisms attached to these particles are also dispersed in the air and can contaminate surgical instruments and materials, such as gloves, gauze and clothing, and can subsequently enter the surgical wounds of the patient, by indirect transfer or direct deposition in the wound itself. Therefore, decreasing particle concentration levels in operating rooms results in a decrease in the number of carriers for organic or microbiological agents [1].

Indoor particles in operating rooms generally have three origins, particles generated inside the operating room, particles from adjacent areas and outdoor particles introduced in the room via the ventilation system.

Few studies have been conducted into the harmful risks associated with outdoor particles that can be introduced in an operating room via the ventilation system. This is worrying, because many large cities hospitals are commonly located in urban areas, with significant air pollution. It is estimated that indoor particle concentrations depend strongly on outdoor particle concentration and follow similar temporal variations as those encountered outdoors. Therefore, knowledge of the factors that control the relationship between indoor and outdoor particle concentrations is particularly important. Particles of outdoor origin, such as combustion products, dust or bio-contaminants, which penetrate indoor hospital environments, can themselves be irritants but they can also act as carriers of absorbed pollutants of indoor origin [1].

Thus, filtering systems constitute a very important defense against the outdoor air pollution, especially in environments which demand a large amount of external air, such as operating rooms. The filtering systems must protect the surgical wound, sterile equipment and occupants against the dangerous effects of outdoor particles. HEPA (High-Efficiency Particulate Air) air filters have been traditionally used in hospital operating. This type of air filter can theoretically remove at least 99.97% of dust, pollen, mould, bacteria and any airborne particles with a size of 0.3 µm.

It is also important to highlight that the influence of indoor sources makes it difficult to directly quantify the extent that outdoor particles contribute to indoor concentrations. For example, under most circumstances, indoor sources or activities conducted indoors can result in increased particle concentration in indoor environments, such that the indoor particle concentrations cannot be directly estimated from outdoor particle concentrations. In other words, the operating room environment is complex and constantly changing, and the concentrations of indoor particles depend on the balance between source and loss processes.

To avoid this problem, the use of mathematical models can be used to study the dynamic behaviour of indoor and outdoor particles in the operating room. These models provide the tools best suited for studying general indoor air quality problems under a wide range of conditions and can improve our understanding of indoor particle dynamics and infection control in the operating room.

Among the main models, the mass balance model can be used to simulate average indoor air pollutant concentrations as a function of outdoor concentrations, building and pollutant characteristics, and indoor sources [2]. In this model, several factors that govern indoor particle concentrations can be described, such as: direct emissions from indoor sources, outdoor particles penetrating indoors as a result of the ventilation and filtration processes, deposition on indoor surfaces, and removal from indoor air by means of ventilation [3].

In this context, the objective of this work was to investigate the effect of the HVAC filtration system on reducing outdoor particle concentration inside an operating room. Also, in order to predict the variations of concentrations and estimate the impact of individual sources on pollutant concentration, a balance mass model was used. Measurements of particles with diameters between 0.3-10 µm were made at the air inlet of the air conditioning system and inside the room. Filters with efficiencies between 65% and 99.97% and combinations of these filter classes were studied.

Methods

The buildings and its ventilation and filtration systems

The measurements were carried out in an operating room with an area of approximately 19 m^2, in a hospital located in the downtown area of São Paulo. The air conditioning system, located in a plant room adjacent to the operating room, was self-contained and it operated with a capacity of 10 TR (Tons of Refrigeration), using absolute filtration (HEPA), with 100% of outdoor air and 8 ACH (Air Changes per Hour). The outdoor air entered into the plant room and was immediately aspirated by the air conditioning unit. The first filtration stage (65%) was located at the entrance of the air conditioning unit, while the second and third filtration stages (85% and HEPA, respectively) were located in a ventilation box, prior to entering the air distribution system. The air then entered the surgical room through supply grills located on the ceiling, above the surgical table. The two supply grills had horizontal jets, which caused a helical mixing of the air. The four return grills were also located on the ceiling. Figure 1 shows an outline of the air distribution system.

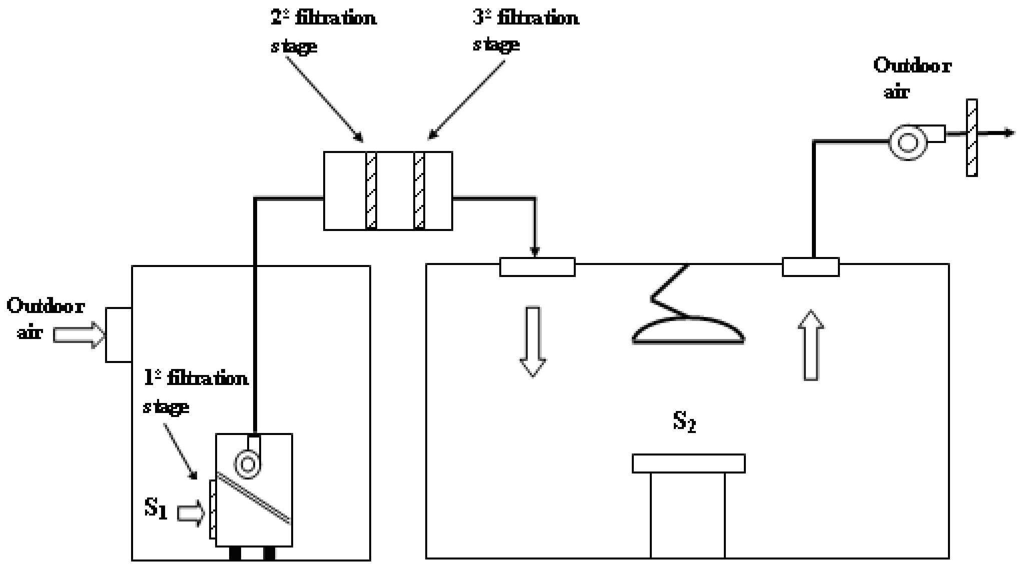

Fig. 1. Schematic representation of the building and its ventilation and filtration systems

Experimental technique

Airborne particle concentrations were measured in six particle size ranges, 0.3-0.5 µm, 0.5-1.0 µm, 1.0-3.0 µm, 3.0-5.0 µm, 5.0-10.0 µm, and >10 µm, with a flow of 0.1 cfm (2.83 L/min). The equipment was calibrated by the manufacturer (MET ONE).

Particle concentration measurements were conducted every 5 minutes, for a duration of 60 seconds, at two locations: upstream of the air conditioning system (S1) for outdoor air and on the operating table (S2) for indoor air (see Figure 1). The measurements were carried out without human activity (surgery) and during working days using four different filter combinations (Table 1) that were replaced after each measurement.

The measurements were performed in five steps as summarized in Table 1:

(i) In Combination F0, the measurements were carried out with the system working without filters. The objective of this step was to measure particle loss on HVAC system components;

(ii) In Combination F1, the system worked only with a 65% efficiency filter located at the entrance of the air conditioning unit (1º filtration stage);

(iii) In Combination F2, the system worked with a 65% efficiency filter (1º filtration stage) and an 85% efficiency filter located in the ventilation box (2º filtration stage);

(iv) In Combination F3, the system worked with a 65% efficiency filter (1º filtration stage) and a 95% efficiency filter in the ventilation box (2º filtration stage); and

(v) In the Combination F4, the system worked with a 65% efficiency filter (1º filtration stage), an 85% efficiency filter in the ventilation box (2º filtration stage) and a HEPA filter (3º filtration stage), respectively.

Table 1 – Filter combinations.

	Combinations
F0	Without filter
F1	65%
F2	65% + 85%
F3	65% + 95%
F4	65% +85% + HEPA

To calculate particle reduction efficiency on the HVAC components, Equation (1) was used:

$$\eta = 1 - \frac{C_{\text{upstream HVAC}}}{C_{\text{operating table}}} \qquad (1)$$

Where:

η = particle reduction efficiency;
$C_{\text{upstream HVAC}}$ = particle concentration at the entrance of the HVAC system (S_1);
$C_{\text{operating table}}$ = particle concentration on the operating table (S_2).

The particle reduction efficiency (filtration efficiency) of the filters was obtained by measuring particle concentration at the entrance of the HVAC system (S_1) and on the operating table (S_2), after subtracting the particle loss on HVAC system.

Modelling technique

In this study, a mass balance model was used to simulate average indoor air particle concentrations as a function of HVAC system, building and particle characteristics, and indoor and outdoor sources. Figure 2 schematically depicts some of the processes that affected indoor particle levels in the operating room studied.

The model assumed the hypothesis of perfect mixing (i.e. a uniform concentration of particles in the whole volume) [4].

In a general way, the basic equation represents the variation of indoor particle concentration in the room volume, over time. It considers that the total number of particles indoors is equal to the sum of the particles introduced from the outside air, as well as the particles generated by indoor sources, less the particles removed by the HVAC system and those removed by deposition on indoor surfaces [5, 6].

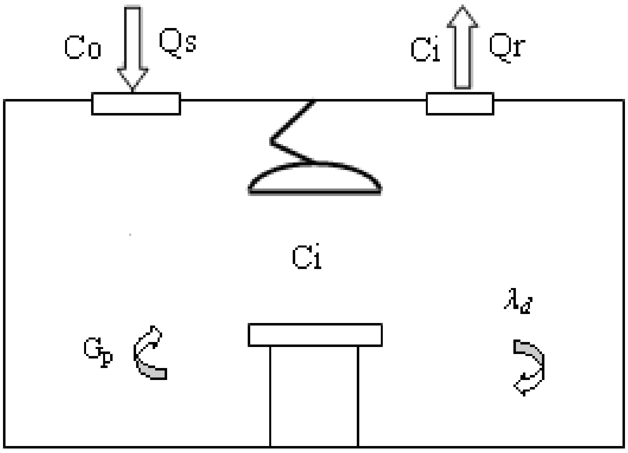

Fig. 2. Schematic representation of indoor particle dynamic processes.

Based on the above assumptions and utilizing the mass balance conception, the variation in particle concentration can be given by Equation (2):

$$V\frac{dC_i(t)}{dt} = \left[(1-\eta)\,Q_s C_o + G_p\right] - \left[Q_e C_i + \lambda_d V C_i\right] \tag{2}$$

Where

C_i(t) = indoor particle concentration at time t (particle/m^3);
C_o = outdoor particle concentration (particle/m^3);
V = volume of the space (m^3);
G_p = particle generation rate (particle/h);
Q_s = airflow from supply air into the room (m^3/h);
Q_e = airflow from the room to the outdoor air (m^3/h);
η = removal efficiency of the HVAC filter;
λ_d = particle deposition rate (/h).

The positive terms are the emission sources in the room and the negative terms are the different removal process from indoor air. The general equation solution of Equation 2 is written as Equation (3):

$$C_i(t) = \frac{Q_s C_o + G_p}{Q_r + \lambda_d V}\left[1 - \exp\left(-\frac{Q_r + \eta Q_s + \lambda_d V}{V}t\right)\right] + C_i\left[\exp\left(-\frac{Q_r + Q_s + \lambda_d V}{V}t\right)\right] \tag{3}$$

Where Ci = initial concentration of particles in the room.

Therefore, it can be seen that the mathematical model developed by means of this method requires a set of input parameters, such as the initial indoor particle concentration, filtration and ventilation characteristics, particle deposition rate etc.

The particle concentration measured indoors at the beginning of the modelled time period was used as the initial concentration (C_i), while the airflows from outside (Q_s) and exhaust air (Q_e) were considered to be equal.

The filtration process was treated in a simplified manner by assuming constant filtration efficiency independent of airflow rate, time and contaminant characteristics.

The deposition rate utilized in this study is based on results from experimental studies which measured the indoor deposition loss rate over a range of conditions [5, 7].

In the current study, the effects of re-suspension were neglected due to the complexity and the lack of experimental data.

In this study, only the presence of people and their activity indoors were considered as an indoor source of particles. The generation rate of particles due to the occupants (G_p) was estimated to be 4,170 (particles/s) per person [5, 8]. A team of four people was considered.

Considering that many of the particles of microbial origin tend to be larger than 1 µm, all simulations were based on particle sizes above 1.0 µm.

It was also considered that contaminants are generated continuously at a steady rate and that no infiltrations or leakages occur. These assumptions are justifiable since spatial contaminant distribution is not required because only the average values are used.

Results

Experimental results

Figure 3 shows the outdoor and indoor particle concentration as a function of size for each combination of filters.

It can be seen that outdoor air is dominated by the smallest particles and the concentrations decreased with the increase in particle size. Outdoor particles 0.3-05 µm had an average concentration of $96.7x10^6$ particle/m^3, which was approximately 4720 higher than particles >10 µm that had the smallest concentration, $2.0x10^4$ particle/m^3.

When the system was operated without a filter (Combination F0) the indoor average concentration for 0.3-0.5 µm particles was $74.3x10^6$ particle/m^3, representing 76.8% of the concentration in outdoor air and for particles >10 µm, it was $4.0x10^3$ particle/m^3, representing only 20% of outdoor concentrations.

For Combination F1, the average indoor particle concentration in the size range 0.3-0.5 µm was $44.7x10^6$ particle/m^3, which was approximately half that of outdoor air and 60% of the concentration for Combination F0.

For Combination F2, the indoor particle concentration for 0.3-0.5 µm and >10 µm particles was $28.1x10^6$ particle/m^3 and $1.6x10^3$ particle/m^3, respectively. Comparing Combination F2 with Combinations F0 and F1, particle concentration in the 0.3-0.5µm size range was approximately 40% and 66%, respectively.

For Combination F3, the indoor particle concentration for 0.3-0.5 µm particles was $23.3x10^6$ particle/m^3, which was very close to the values for Combination F2.

Finally, the Combination F4 produced the lowest indoor particle concentration for all filter combinations. For 0.3-0.5 µm and >10 µm particles, the concentration was $5.6x10^4$ particle/m^3 and less than $1.0x10^3$ particle/m^3, respectively. Compared with outdoor concentrations, these values were equivalent to 0.06% and 3% of outdoor values for 0.3-0.5 µm and >10 µm particles, respectively.

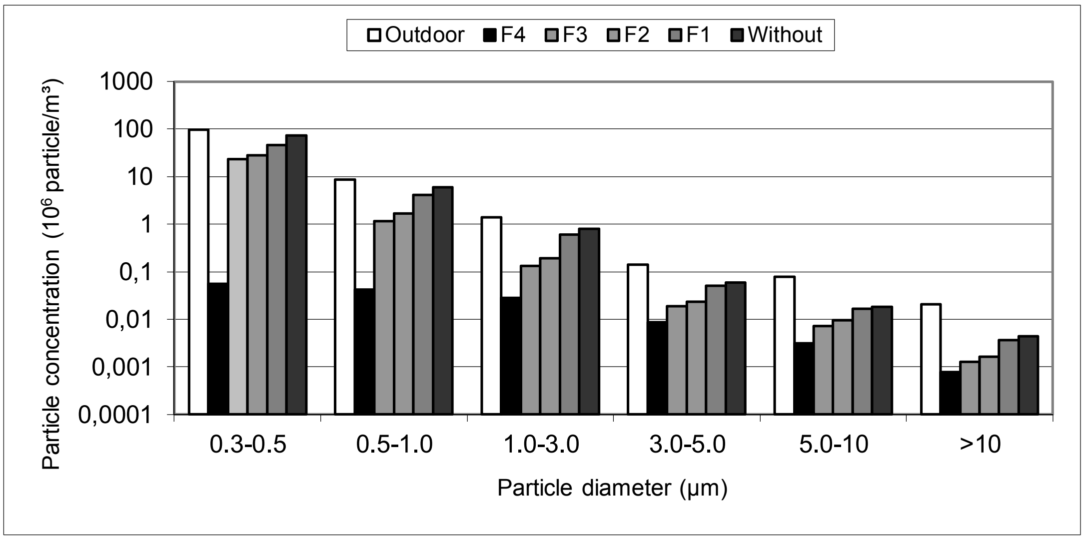

Fig. 3. Particle concentration as a function of size for all combinations.

Figure 4 shows the effects of the HVAC systems on particle reduction by deposition. For this analysis the system worked without filters. In this study it was considered that particle deposition occurred on the surfaces of ducts, fan and cooling coil.

The results show that the percentage of particle reduction increased with particle size. For example, for particles 0.3-0.5 µm in diameter, particle reduction was about 23%, while for particles >10 µm it was about 76.6%. It is important to highlight that the difference between particle size 5.0-10.0 µm and >10.0 µm was not significant.

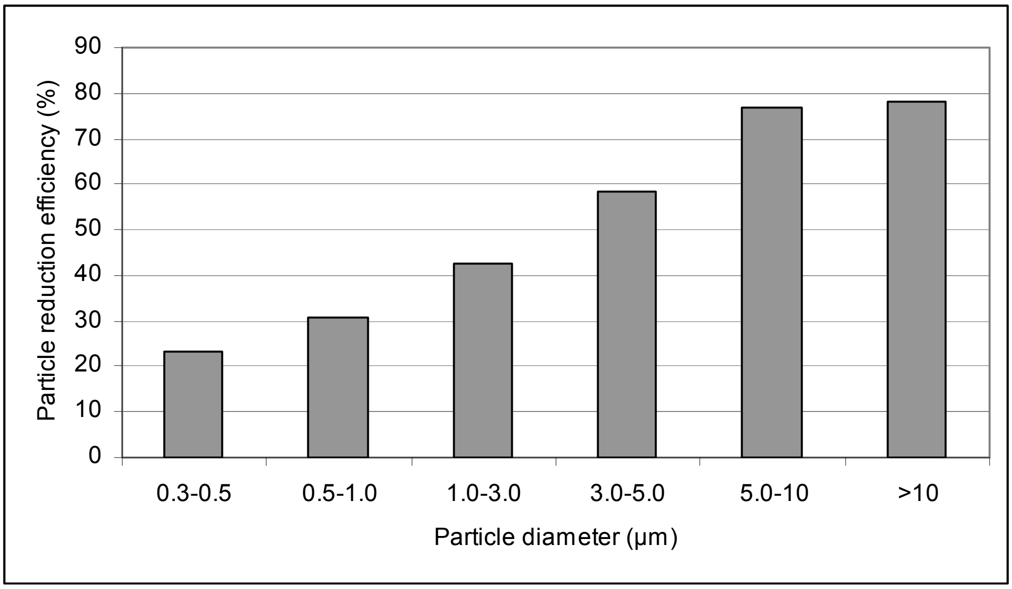

Fig. 4. Particle reduction in HVAC components without filters

Figure 5 shows the particle reduction efficiency of different filters, considering only the particles removed by the filters.

Combination F4 showed the best filtration efficiency for all particle sizes; however as particle size increased the performance of other filters increased. Strangely, the efficiency for Combination F4 decreased with an increase in particle size.

Combination F4 showed 99.9% removal for 0.3 - 0.5 µm particles and 99.06% for 0.5 - 1.0 µm particles. The worst performance was for >10 µm, with an efficiency of 96.2%. For Combination F3, the best performance was achieved for >10 µm particles (93.8%) and the worst performance was for 0.3 - 0.5 µm particles (75.9%). Combination F1 and F2 also had the best performance for >10 µm particles (82.1% and 90.1%, respectively), whilst Combination F1 showed very poor efficiency for 0.3 - 0.5 µm particles (52.8%).

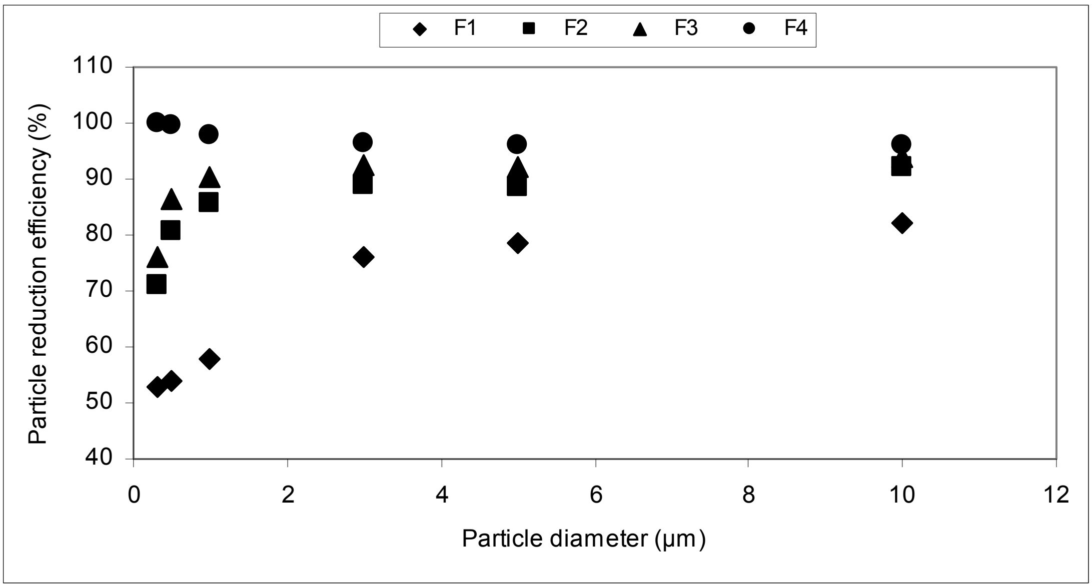

Fig. 5. Particle reduction efficiency on filters.

Figure 6 shows a comparison of indoor/outdoor ratios for all filter combinations and for each particle size. In general, it can be seen that for Combination F4 the indoor/outdoor ratio increased with particle size and for other combinations the indoor/outdoor ratio decreased with particle size. For this combination, indoor particle concentration in the range 0.3 - 0.5 µm was substantially lower than outdoor particle concentration with an indoor/outdoor ratio close to 0. For particles 0.5 - 1.0 µm, Combination F4 continued to have a good indoor/outdoor ratio (0.005). For 1 - 3 µm, 3 - 5 µm and 5 - 10 µm size ranges, Combination F4 showed a slight increase in indoor/outdoor ratio (0.020, 0.035, and 0.040, respectively). For particles >10 µm, the indoor/outdoor ratio decreased again and reached 0.0379.

Combinations F2 and F3 resulted in very close indoor/outdoor ratios in all particle sizes. For example, the indoor/outdoor ratios were 0.241 and 0.290 for 0.3 - 0.5 µm particles, respectively. For particles >10 µm, it was 0.062 and 0.079, respectively.

Combination F1 showed the biggest indoor/outdoor ratio, in size 0.3 - 0.5 µm it was 0.472 and for >10 µm it was 0.179.

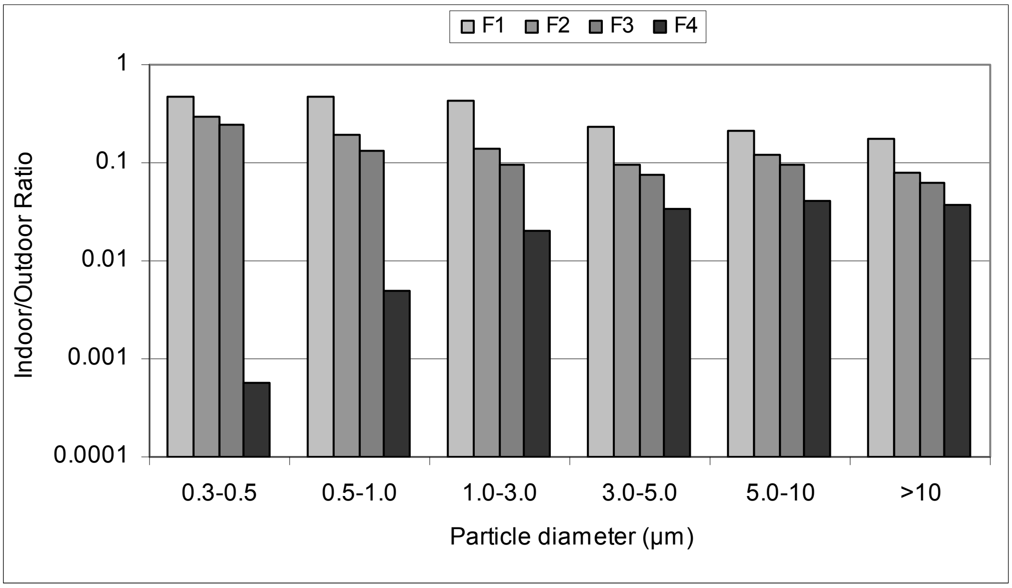

Fig. 6. Indoor/outdoor ratio as a function of particle diameter.

Modelling results

Figure 7 shows temporal variations of measured and predicted outdoor and indoor particle concentration for particles above 1.0 μm, for each filter combination without indoor sources. It is important to keep in mind that indoor particle concentrations were calculated from Equation 3, which was applied for each filter combination.

From Figure 7 it can be seen that for all combinations, the variability of the predicted indoor concentration depended on the outdoor concentration. It can also be seen that filters with higher removal efficiencies resulted in considerably decreased indoor particle concentrations.

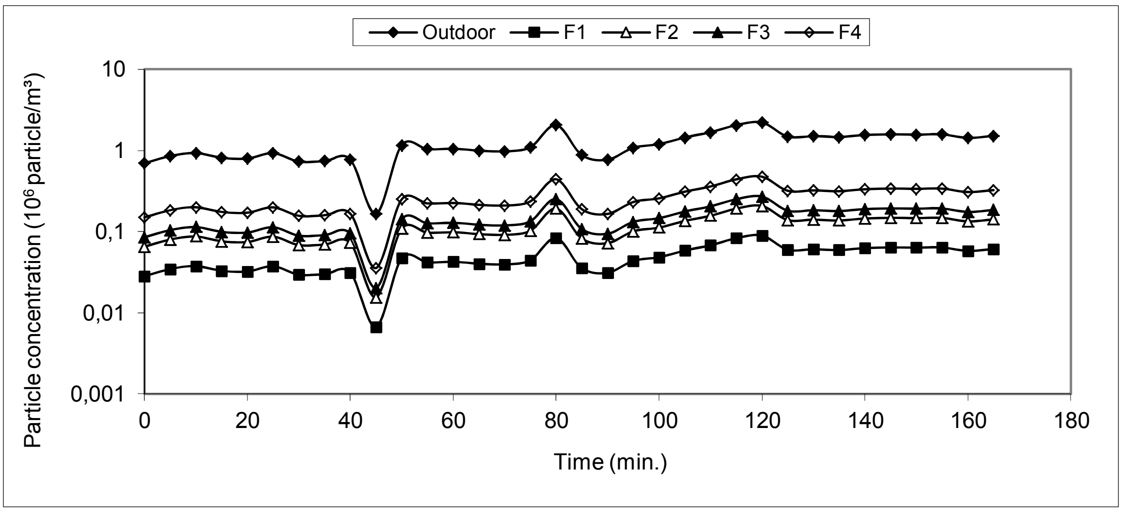

Fig. 7. Temporal variations of outdoor and indoor particle concentration.

Figure 8 presents a comparison of numerical and experimental results with and without indoor sources for Combination F4 and for particles >1.0 μm particles. It can be seen that there was good agreement between the numerical and experimental results without indoor sources.

The results also demonstrated that human activities strongly influenced indoor particle levels, which were approximately 4.5 times higher than the levels measured without human activities. The average particle concentration with and without human activities was 2.5×10^5 particle/m^3 and 5.5×10^4 particle/m^3, respectively.

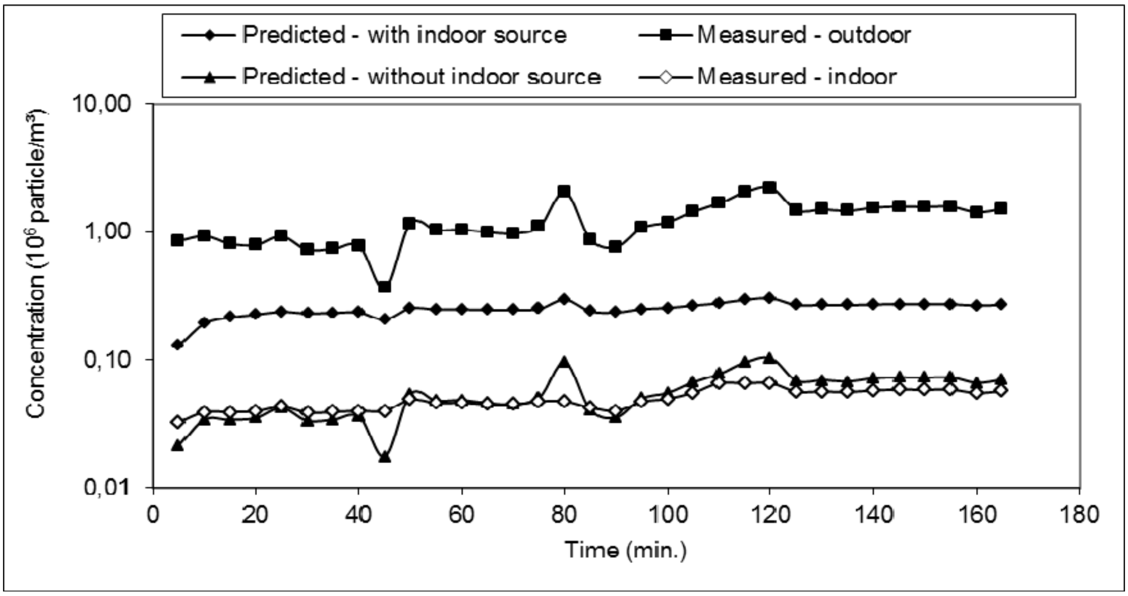

Fig. 8. Comparison of numerical and experimental results.

Figure 9 compares the percentage of particles generated by human activities and outdoor air for different filter combinations and for particles above 1.0 µm. These results show that when the filter efficiency increased, the effect of outdoor sources decreased while the effect of indoor source increased.

With a high efficiency filter, the impact of outdoor air was less than the impact of the surgical team, which was the dominant indoor source of particle generation. For example, for Combination F4, outdoor air contributed 2.51% of the indoor concentration, while the surgical team contributed 97.49%.

For Combination F1, outdoor air contributed 41.8% of the indoor concentration, while surgical team contributed 58.2%.

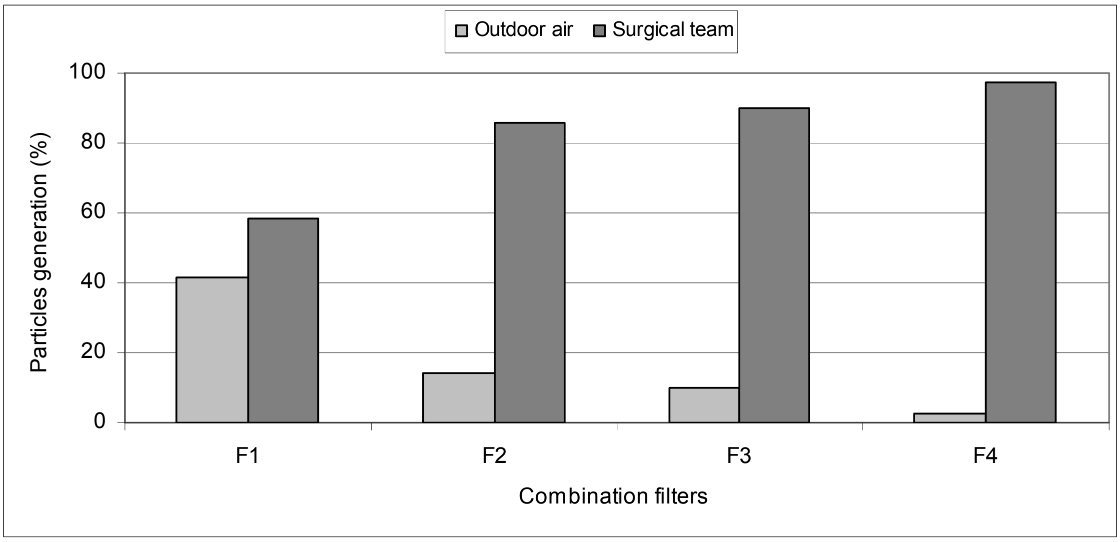

Fig. 9. Particles generated by human activities and outdoor.

Figure 10 shows a comparison between the percentage of particles removed by deposition and the HVAC exhaust, for particles >1.0 µm using Combination F4 filters. It can be seen that the most important removal mechanism was the HVAC exhaust system, removing 79.6% of the total particle generated inside the operating room, with deposition loss contributing 20.4%.

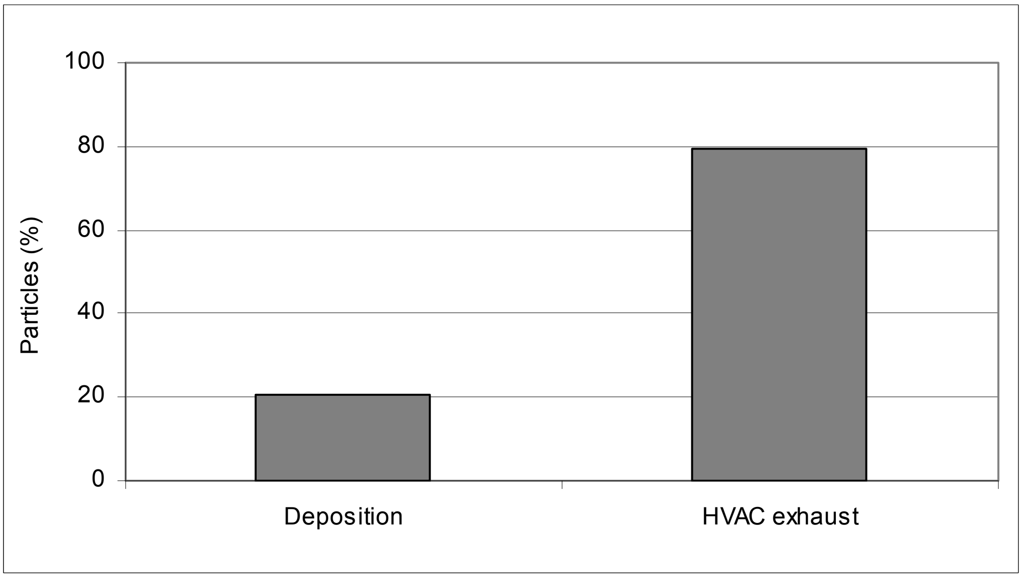

Fig. 10. Particle removed by deposition and HVAC exhaust system.

Figure 11 illustrates the results of simulation on indoor concentration, considering indoor sources and air changes per hour (ACH). It can be seen that increasing ACH to high levels resulted in an excellent removal of particles.

The results also show that the difference in indoor particle concentrations between the lowest (4 ACH) and highest (25 ACH) air changes per hour was approximately 4.5 times lower under the highest ACH.

The American Institute of Architects (AIA, 2006), typically recommends 12 - 25 ACH in operating rooms. The suggested ACH is 15 ACH for systems that use all outdoor air and 25 ACH for re-circulating air systems. The operating room system in this study used all outdoor air at 8 ACH, which is 33% below the recommended standard. According to the simulations, if the room was working within the recommended standard, the concentration of particles would be 71% lower.

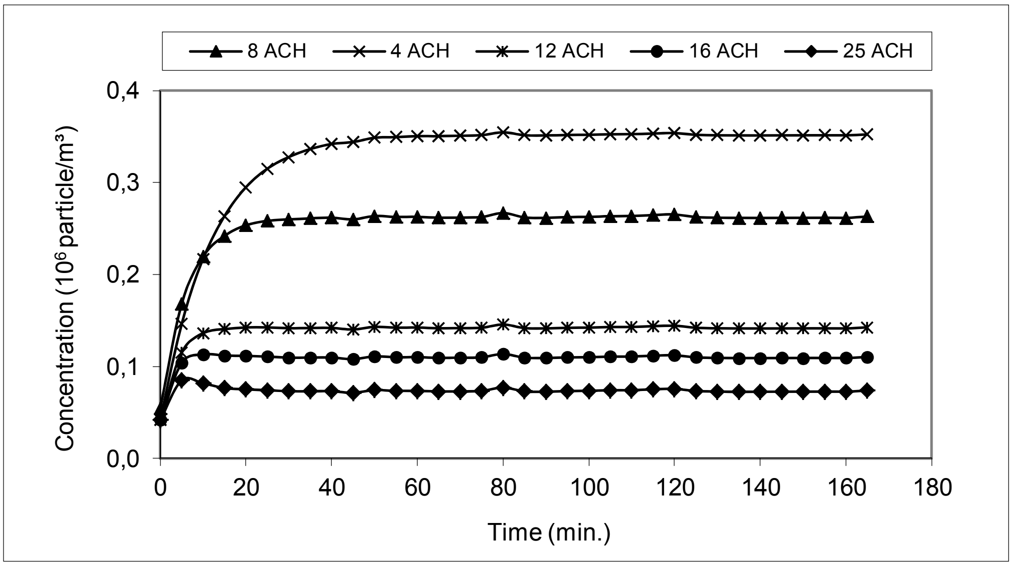

Fig. 11. Effects of air changes rate on particle concentration.

Discussion

Experimental investigations

The results showed that in the absence of indoor particle sources, indoor particle concentrations will often be lower than outdoor concentrations as a consequence of particle removal processes, such as particle removal by filtration systems and particle deposition on indoor surfaces. Small particles, principally those between 0.3 - 0.5 µm, had a major influence on indoor particle concentration. This was expected since the hospital studied is located downtown, close to a heavy-traffic area. This finding has been observed in many prior studies. According to Morawska et al. (1998), the greatest numbers of atmospheric aerosol particles are in the size range < 1 µm [1]. Similarly, according to the United States Environmental Protection Agency (EPA, 1996), the small particles (< 1 µm) in outdoor air are mainly produced from combustion processes and through photochemical reactions [9].

This finding highlights the importance of understanding the relationship between indoor and outdoor air in operating rooms. According to Morawska et al. (1998), particles of outdoor origin, such as combustion products, dust or bio-contaminants, can themselves be irritants but can also act as carriers of biological agents of indoor origin [1]. In a study by Jamriska et al. (1998), the authors stated that the performance of filtration systems in an operating room is the most critical parameter in reducing general airborne particle concentration levels from outdoor sources [10].

In this study, it was demonstrated that the effective removal of small sized particles required a higher-efficiency filter. But, as particle size increased, the benefits of high efficiency filtration decreased, presumably because the efficiency of other filters, which have a low efficiency for small particles, increases with particle size. According to Hinds (1998), a minimum in the filtration efficiency curve is often observed in the particle diameter range 0.1–1.0 µm [11]. This finding is very important because many of the particles of microbiological origin tend to be larger than 1 µm, indicating that medium to high-efficiency filters should be effective in removing such large proportions of bacteria and spores, and that HEPA filters may represent over-filtering, even for health care facilities [12]. Luciano (1984) have shown that 99.9% of all bacteria present in a hospital are removed by filters with an efficiency of 90 to 95% [13]. According to the authors, this is because bacteria are typically present in colony-forming units that are larger than 1 μm [13].

It could also be seen that in Combination F4, which operated with a HEPA filter, an increase in particle size caused decreased filtration efficiency. This finding does not agree with generally accepted filtration theory, which suggests that normally the filter efficiency increases with particle size. A similar result was obtained by Fisk et al (2002) during the measurement of particle concentrations and size distributions with a normal and high efficiency air filter in a sealed air-conditioned office building [12]. In this study, particle concentration above 0.7 μm increased with particle size when a HEPA filter was used [12]. The reason for this is that, for Combination F4, the impact of outdoor air was smaller and therefore, the impact of internal sources was more easily expressed.

Additionally, the existence of a possible indoor source could be seen clearly by analysis of the indoor/outdoor ratio. The indoor/outdoor ratio is an indicator for evaluating the difference between indoor and outdoor levels. The average indoor/outdoor ratios for most filter combinations indicated that the contribution of outdoor sources to indoor particle concentration was higher in the smaller size ranges. For Combination F4, the indoor/outdoor ratio increased with particle size, indicating the presence of an indoor particle source as previously commented. The results also indicated that, due to filter properties, the indoor/outdoor ratio was not uniform for all particle sizes.

After analysing the effects of the HVAC components and ducts on indoor particle concentration reduction, the results showed that a good fraction of outdoor particles were removed from the air flowing through HVAC systems by deposition on the surfaces of ducts and on cooling coils. This evidence strengthens the previous comments about indoor sources. The particles removed by the HVAC components and on duct surfaces increased with particle size. For example, the measurements showed that for 0.3 - 0.5 μm particles, particle reduction was about 23%, while for >10 μm particles, the loss was about 78%. These results agree with the work of Wallin (1993), who concluded that approximately 7% of 10 μm particles would deposit on new clean surfaces of a duct system and that the depositional losses would increase to nearly 100% over a period of 10 years, as the duct surfaces become rough due to accumulation of particles [14]. This is a cause for concern because bacteria and fungi can deposit on HVAC surfaces and grow if sufficient water is present, and those agents may amplify the concentration of bio-aerosols in the air stream and act as a potential source of indoor air contamination in the operating room.

Modelling investigations

The predicted temporal variations of outdoor and indoor particle concentration for each filter combination indicated that, due to the absence of indoor sources, indoor particle concentration followed the same trend as outdoor concentrations. This confirms that, in case of no apparent indoor sources, outdoor air has a strong influence on indoor air, and that as particle filter efficiency increases, the particle concentrations from outdoor source would decrease inside the room.

On the other hand, in the case of existing indoor sources, the modelling results showed that depending on filter efficiency, the indoor particle levels were strongly influenced by indoor human activities in addition to outdoor levels. That is, when low performance filters were used, outdoor air was the main contributor and when the system operated with high performance filters, the surgical team was the main contributor. This finding is in agreement with Yeh et al. (1995), who suggested that the surgical team is the largest source of generation of particles inside an operating room [15]. This is easy to understand since during indoor human activities, skin, hair and other substances are released from the body and clothing. This is a concern because when an aerosol contaminant is introduced into an indoor environment, it can remain in the air, deposit on interior surfaces or attach to dust particles already present. In addition, many particles emitted from the body can be contaminated by bacteria. According to Roberts et al. (2006), skin flakes are relatively large particles (4 - 25μm), and once released or re-suspended, can transport staphylococci [16]. Additionally, human activity, such as walking and cleaning, can re-suspend contaminated particles. This confirms that the number of personnel in the operating room should be minimized and that the traffic in and out of the operating room should also be restricted.

The results showed that the two most important processes that reduced the indoor particle concentration were deposition on indoor surfaces and the HVAC exhaust system. Deposition removed about 20%, while the HVAC exhaust system removed about 80% of the total particles generated inside the operating room.

It is important to highlight that in an operating room the deposition is worrying because contaminated particles can deposit surgical instruments and materials, such as gloves, gauze and clothing, and can subsequently enter the surgical wounds of the patient, by indirect transfer or direct deposition in the wound itself. Additionally, particles deposited on the floor can also represent a risk by re-suspension as commented previously. Particle deposition is a complex phenomenon and is rarely studied. According to Thatcher et al (1995), the magnitude of the deposition loss rate can be influenced by many factors including: particle size, shape and density; surface area and orientation; surface roughness; surface-to-air temperature difference; surface-particle charge difference; and air speed [17].

With respect to removal by the HVAC exhaust system, this finding suggests the importance of a properly functioning HVAC exhaust system in the operating room. For example, the air should leave the room through the HVAC exhaust without the obstruction of furniture etc.

It was also observed that ACH affected indoor particle concentration, as indicated by the simulation. For example, at higher ACH, indoor particle concentration was smaller. A study by Memarzadeh et al (2004), showed that increasing the ACH in an operating room reduces the amount of contaminated air in a space and, therefore, reduces the risk of infection for the patient [18]. According to Hussen et al. (2005), this behaviour is principally due to the effects of particle deposition on indoor surfaces and their residence time indoors [19]. For example, at lower ACH, the residence time of particles in the indoor environment is longer. Hence, by providing a minimum ACH, the contaminants in the operating room are not only diluted, but the surgical team is provided with fresh air for breathing. However, ACH can also significantly affect particle concentration in the room, for both outdoor and indoor particle sources. That is, if the filtering system is not appropriate, a higher supply airflow rate can significantly affect the indoor concentration of particles originating from the outdoor air. Additionally, different airflow rates lead to different air velocities in the room, which may affect airflow pattern and particle spatial distribution. This would influence particle pollution levels, as well as the location of particle sources. This suggests that the influence of ACH on particle concentration in the operating room needs further study, combined with the influence of the location of particle sources.

Conclusion

This work investigated the impact of the HVAC filtration system and indoor particle sources on the relationship between indoor and outdoor airborne particle size and concentrations in an operating room. A mass balance model was used to aid the interpretation of the impact of individual sources on indoor concentration. Owing to the good agreement between experimental and numerical results, the contribution of each parameter on indoor particle concentration could be determined by comparing the measured concentration with the simulated concentration. Through the experimental and numerical results, it was possible to conclude that:

- Without strong indoor particle sources, indoor particle concentrations will often be lower than outdoor concentrations as a consequence of particle removal processes.
- For small particle sizes, the use of high efficiency filtration is the best alternative, because it dramatically reduces the impact of outdoor air on indoor air.
- When filters with low efficiency were used, the indoor particle concentration of small particle sizes was high compared to outdoor concentration levels.
- High efficiency filters would not be expected to decrease the risk associated with indoor particles larger than approximately 1 μm in size, because normal filters are relatively efficient for these large particles. Many intact bio-aerosols may be larger than 1 μm.
- A significant portion of the outdoor particles that pass through the HVAC system are removed by depositing on components and ducts, and this increases with particle size.
- Experimental results provided an indication of the existence of non-evident indoor particle sources, for particles larger than 1 μm.
- Numerical analysis showed that, when the system was operated with a high efficiency filter, indoor particle levels were strongly influenced by indoor human activities.
- Deposition on surfaces was an important factor that affected particle concentration inside the operating room.
- The HVAC exhaust system had a strong effect on the reduction or elimination of indoor particles.
- Indoor particle concentration decreased with increasing ACH, as indicated by the simulation results.

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