Impact of Filtration Conditions on Air Quality in an Operating Room

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Abstract
The aim of this study was to assess the impact of ventilation and filtration conditions on particle concentrations in an orthopedic operating room. Total particle, viable particle, and CO2 concentration were measured under three different situations, namely before air filter replacement, after air filter replacement, and in an operating room with a new air conditioning system. Before air filter replacement, the mean values of airflow, total particle concentration, and viable particle concentration were 706 m3/h, 15.0 × 10^6 ± 4.0 × 10^6 particles/m3, and 57 CFU/m3, respectively. After replacement, the airflow increased to 1954 m3/h, and total and viable particle concentrations decreased to 0.4 × 10^6 ± 0.2 × 10^6 particles/m3 and 24 CFU/m3, respectively. In the room with a new air conditioning system, the airflow was 2051 m3/h, and total and viable particle concentrations were 0.3 × 10^6 ± 0.1 × 10^6 particles/m3 and 15 CFU/m3, respectively. The CO2 levels were 663 ppm (before), 659 ppm (after), and 574 ppm (new room). The results showed that inappropriate or no maintenance of filters in an air conditioning system had significant negative effects on indoor air quality in operating rooms. Air conditioning systems operating with saturated filters can be affected by pressure drop, which can lead to a reduction in airflow, thereby resulting in an increase in the average total particle and viable particle concentrations and the risk of infection in operating rooms. However, the results showed that the CO2 concentration was not affected by the filter replacement.

Article Highlights
• Improper maintenance of the air filters poses negative effects in operating rooms.
• Particles remain inside the room with less air exchange caused by saturated filters.
• Change in filters produces a greater effect on air quality in operating rooms.
• CO2 concentration generated by the people may not be affected by the filter replacement.

Keywords Indoor particles · Total particle · Viable particle · CO2 concentration · Filtration system · Operating room

Introduction
Indoor air quality in operating rooms is a matter of great concern for patients and medical personnel (Dascalaki et al. 2008), especially because of the presence of a vast array of air contaminants, such as chemicals from medical gases used for anesthesia, disinfection and sterilizing substances, and particles of skin debris, lint, respiratory droplets, and aerosols (Gormley et al. 2017). Given this diversity of sources, knowledge of the variation in indoor particle concentrations in operating rooms as well as the factors that affect these variations is important to control the incidence of surgical site infections. According to Pereira et al. (2012), a decrease in particle concentrations can result in a decrease in the number of carriers of organic or microbiological agents in operating rooms and can consequently decrease the risk of infection. Microbiological contamination of operating room air, which is commonly caused by contaminated skin scales released by the surgical team, is generally considered to be the main risk factor for surgical site infection in clean
surgeries (Pereira et al. 2013; Landrin et al. 2005). For example, bacteria such as Staphylococcus aureus are continuously released into the air by operating room personnel and can subsequently precipitate onto the surgical site. These organisms cause the majority of infections in prosthetic implant surgeries, such as hip and knee replacements (Gosden et al. 1998). Additionally, according to their size, many microorganisms that are present in an operating room can be broadly classified, as follows: bacterial cells and spores (0.3–10 μm in diameter), fungal spores (2.0–5.0 μm), and viruses (0.02–0.30 μm) (Morawska, 2006; Fernstrom and Goldblatt 2013).

Filtration and air exchange with the outdoor air plays a key role in maintaining acceptable air quality in operating rooms. Indoor particle concentrations can be decreased by exhausting and diluting the return air with outdoor air (Simmons et al. 1997; Cole and Cook 1998). By means of air renewal, a significant decrease in the pollutants generated in the room can be obtained to keep them below the threshold levels. Dilution ventilation requires the system to condition the outdoor air before it is introduced into the room. Outdoor air usually contains contaminants, such as bacteria, pollen, insects, soot, ash, and dust. These contaminants can penetrate buildings, thereby influencing indoor particle concentrations. Filtration systems constitute a very important defense against outdoor air pollution, especially in environments that demand a large amount of external air, such as operating rooms. The filtration systems must protect the surgical wound, sterile equipment, and occupants against the dangerous effects of outdoor air pollution, especially in environments with high-efficiency filters use monitoring of the pressure drop increase through the filters or the electric current increase energy consumption, air filters need to be replaced periodically. However, the criteria and the frequency of filter replacement can vary due to the fluctuation in the debris-accumulation rate in the air filters. Current manufacturers recommend the replacement of air filters every 3 months (Alsaleem et al. 2016). In the case of high-efficiency filters, this criterion is not feasible due to the costs involved. Thus, many installations with high-efficiency filters use monitoring of the pressure drop increase through the filters or the electric current increase on the fans (Yang et al. 2007).

To prevent HVAC (heating, ventilation, and air conditioning) performance degradation and malfunction that can increase energy consumption, air filters need to be replaced periodically. However, the criteria and the frequency of filter replacement can vary due to the fluctuation in the debris-accumulation rate in the air filters. Current manufacturers recommend the replacement of air filters every 3 months (Alsaleem et al. 2016). In the case of high-efficiency filters, this criterion is not feasible due to the costs involved. Thus, many installations with high-efficiency filters use monitoring of the pressure drop increase through the filters or the electric current increase on the fans (Yang et al. 2007).

Normally, the level of CO₂ that is generated in rooms can be considered as a good indicator of the efficiency of the air conditioning system in the process of air renewal (Spagnoli et al. 1996). CO₂ is a metabolic gas that is expelled naturally as a human respirational sub-product. Indoors, the recommended limits should be below 1000 ppm (ASHRAE 2019). According to Karthikeyan and Samuel (2008), CO₂ concentration can also be an indirect indicator of the occurrence of post-operative wound infections.

Few published studies have examined the impact of filtration conditions on particle and CO₂ concentration levels in operating rooms.

In this context, to identify the impact of the filtration system on indoor contamination in an orthopedic operating room, we measured the total particle, viable particle, and CO₂ concentration in an old operating room before and after the air conditioning filters were replaced as well as in a new operating room that had a new filter and normal airflow.
Methodology

The study was conducted in an orthopedic hospital located in São Paulo, Brazil, and was approved by the Ethics Committee of the Institute of Orthopedics and Traumatology under protocol number 109506.

Study Design

This study was conducted in two operating rooms: one in which the air filter of the HVAC system was poorly maintained. In this room, the filter of the HVAC system was replaced every year. However, due to contract problems with the maintenance company, the HVAC system had been running for approximately four and a half months without a filter replacement. The other operating room had a newly installed HVAC system. Both rooms were placed in the same surgery center.

The first round of measurements was performed 2 weeks before the filters were replaced (Case 1), that is, approximately 4 months after the filter replacement period had expired. The second set of measurements was carried out 1 week after filter replacement (Case 2). The results obtained in Cases 1 and 2 were compared with the measurements in another operating room with a new HVAC system (Case 3).

Both operating rooms had the same layout: the room area was approximately 28 m² with a height of 2.7 m (Fig. 1); they were designed according to the Brazilian standard ABNT NBR 7256 (ABNT 2005) (Table 1).

The distribution system in both rooms was laminar (unidirectional) and the a filter package with three filters was used: first filter with an efficiency of 30%, second filter with an efficiency of 90%, and a third filter, with absolute filtration [high-efficiency particulate air (HEPA)]. The system operated at an air renewal rate of 30% of the outdoor air.

Five major orthopedic surgeries were conducted for each of these cases. In this study, all measurements were performed under the same conditions for the three cases. In other words, all measurements were performed during similar surgeries, involving approximately the same number of people inside the room. In addition, during the measurements, all the doors of the operating room were kept closed, eliminating the possibility of infiltration of pollutants from adjacent areas.

Table 1  Brazilian standard ABNT NBR 7256 recommendation

| Airflow and psychrometric parameters | ABNT NBR 7256 |
|-------------------------------------|---------------|
| Airflow                             | 2100          |
| ACH                                 | 28            |
| Temperature (°C)                    | 18-22         |
| Relative humidity (%)               | 45-55         |
Measurements of particle concentrations were conducted using real-time, size-resolved optical particle counters, which were calibrated by the manufacturer (Met One, Model HHPC-6). These portable (27 × 10 × 5 cm) particle counters have a flow rate of 2.83 L/min, which is able to measure the particle number concentration in the following range: 0.3–0.5 µm, 0.5–1.0 µm, 1.0–3.0 µm, 3–5 µm, 5–10 µm and > 10 µm. Since the aim of the present study was to analyze the impact of filtration conditions on air quality, the results in terms of particles were reported as the sum of the concentrations measured for all six channels (0.3–10.0 µm), which represent the size range of typical airborne infectious particles in operating rooms.

For each surgery, measurements were recorded every 5 min with a 1 min sampling time throughout the surgery. The first measurement was recorded in the empty room soon after the cleaning procedure and before the patient’s arrival. The measurement equipment was placed on the surgical lamp arm above the patient. In this position, the convective currents due to the temperature of the surgical lamps did not affect the measurements. Furthermore, with a vertical flow system, heat generated by the surgical lamps created only minor air turbulence (Zoon et al. 2010).

Airborne viable bacteria were collected using a single-stage Andersen air sampler. The instrument was placed 1.5 m above the floor at a distance of 1 m from the surgical area. Samples were collected every 30 min at an air sampling rate of 28.3 L/min throughout the surgeries. The samples were incubated in blood agar plates (Newprov) for 48 h at 37 °C; the colony forming units were counted by direct visual observation and expressed in CFU/m³ (Pereira et al. 2012; Andersen 1958). To identify bacteria, colonies were stained for a Gram stain test (Newprov), followed by the biochemical analyses for S. aureus.

Bacterial Collection and Identification

Air Velocity

The airflow (m³/h) was obtained in each case by measuring the velocity of the air at several points of the laminar diffuser and multiplying the average by the area of the air passage. The equipment used to measure air velocity was the Airflow TA-5, which has a measurement range of 0–20 m/s, resolution of 0.01 m/s, and measurement uncertainty of ±2%.

CO₂ Concentration

The CO₂ concentration in the operating rooms was recorded at 5 min intervals using a fixed monitor at breathing height, which was approximately 1.7 m above the floor. The monitor was tested and calibrated in the laboratory before the field measurements were conducted. For CO₂ concentration, the measurement uncertainty of the instrument (Instrutemp) was ±30 ppm (±5%) of the reading (0–10000 ppm). As the main source of CO₂ emissions in the operating room is anthropogenic, the number of personnel was also considered in the study. Psychrometric parameters, such as temperature and relative humidity, were also measured with the same instrument, and the airflow was assessed with a hot wire anemometer (Dantec 54T33).

Data Analyses

Data were analyzed using SPSS version 20.0 (SPSS 2015) as well as descriptive and inferential statistics. Descriptive statistics was used to check the maximum and minimum values, and dispersion of data was reported using standard deviation. Mann–Whitney U and Kruskal–Wallis tests were used to compare mean particle (bacteria and total particle) concentrations. The significance level was defined as p < 0.05 for all tests.

In this study, the results are accompanied by the standard error of the mean (ISO/IEC 2008).

Results

Table 2 summarizes the airflow rate and psychrometric parameters measured in all three cases. The airflow increased from 706 ± 14 m³/h (9.3 ± 0.2 ACH) before the filters were replaced (Case 1) to 1954 ± 40 m³/h (25.8 ± 0.5 ACH) after the filters were replaced (Case 2). This value was very close to the airflow in Case 3, which was 2051 ± 41 m³/h (27.1 ± 0.5 ACH) and close to the Brazilian standard ABNT NBR 7256 (2005) (Table 1). For Case 1, the airflow rate was 66.4% below the recommendation; for Case 2, it was 7%; and for Case 3, it was near 2% of the Brazilian standard.
Figure 2 presents the impact of the filter on the total particle count, which was assessed before and after the air conditioning filters were replaced (Cases 1 and 2, respectively) and in the new room (Case 3). It can be seen from this figure that the change in the filter significantly decreased the particle concentration inside the room. For Case 1, the average particle concentration was $15.0 \times 10^6 \pm 4.0 \times 10^6$ particles/m$^3$. For Case 2, the average decreased to $0.4 \times 10^6 \pm 0.2 \times 10^6$ particles/m$^3$, thereby indicating that the average total particle concentration decreased by approximately 97%. Statistical analysis showed that the difference between the average particle concentrations for these two cases was significant ($p < 0.05$). For Case 3, the particle concentration had an average of $0.3 \times 10^6 \pm 0.1 \times 10^6$ particles/m$^3$. Comparing the average particle concentration for Case 1 with that of Case 3, the latter was approximately 98% lower than the former ($p < 0.05$). The average particle concentrations for Case 2 and Case 3 were close, which was already expected, as all the parameters, according to Brazilian standard ABNTNBR 7256 (2005), for both rooms were almost the same.

Figure 3 shows the concentration of viable particles measured before (Case 1) and after (Case 2) the air conditioning filters were replaced in the old room and in the new room (Case 3). The concentration of viable particles measured in Case 1 was notably higher than that measured in Case 2 and Case 3. The average particle concentrations were 57 ± 8 CFU/m$^3$ in Case 1, 24 ± 7 CFU/m$^3$ in Case 2, and 15 ± 3 CFU/m$^3$ in Case 3. On comparing the averages between Case 1 and Case 2, the viable particle concentration in Case 2 was lower, thereby indicating that the average total particle concentration was almost half (53%). Statistical analysis showed that the difference was significant ($p < 0.05$). The average viable particle concentration was 72% higher before the filters were replaced (Case 1) than in the new room (Case 3). This difference was statistically significant ($p \leq 0.05$). However, the differences between the average particle concentrations after the filters were replaced (Case 2) and in the new room (Case 3) were not significant ($p > 0.05$).

Table 3 presents the gram-negative and gram-positive bacterial percentages, the prevalence of coagulase-negative Staphylococci, and the concentrations of CO$_2$ measured during all the surgeries. The concentration of gram-positive bacteria was greater than that of gram-negative bacteria. The prevalence of gram-positive bacteria was not affected by filter replacement ($p > 0.05$); that is, it continued to remain high at 91 ± 4% for Case 1, 92 ± 5% for Case 2, and 90 ± 6% for Case 3.

The samples were also tested for coagulase-negative bacteria to differentiate *S. aureus* from coagulase-negative Staphylococci. The prevalence of coagulase-negative Staphylococci remained high in all surgeries. For Case 1, the average was 86 ± 3%; for Case 2, 67 ± 16%; and for Case 3, 76 ± 9%. It is important to highlight that coagulase-negative Staphylococci are the most common cause of nosocomial infections.

Table 3 shows that the CO$_2$ concentrations were practically not affected by the filter replacements. In the new room, CO$_2$ concentration was kept constant. The average CO$_2$ concentrations were 663 ± 21 ppm in Case 1, 659 ± 28 ppm in Case 2, and 575 ± 4 ppm in Case 3.

**Discussion**

Before the filters were replaced, the system operated at an airflow of 706 m$^3$/h (9.3 ACH), and the average total and viable particle concentrations inside the room were $15.0 \times 10^6 \pm 4.0 \times 10^6$ particles/m$^3$ and 57.4 CFU/m$^3$, respectively. After the replacement, the airflow increased to 1954 m$^3$/h (25.8 ACH), and the respective averages of particle
concentrations decreased to $0.4 \times 10^6 \pm 0.2 \times 10^6$ particles/m$^3$ and 24.5 CFU/m$^3$, respectively. The Brazilian standard ABNT (2005) recommends 2800 m$^3$/h (28 ACH) in an operating room. These results showed that with filter replacement, the airflow inside the room increased by almost three times, and viable particle concentration and total particle concentration decreased by 53% and 97%, respectively.

The differences between the average particle concentrations after the filters were replaced and in the new room were around 60%. However, it is important to highlight that this difference was due to the fact that in the new room there was no dust or debris accumulated from years of use within the duct system. Thus, this is the reason for the large difference in the particle concentration between the two rooms.

These results suggest that inadequate or ineffective ventilation, caused by dirty or saturated filters, results in elevated contaminant levels. This is because the particles remain inside the room with less air exchange. On the other hand, proper ventilation with greater airflow causes them to follow the airflow pattern, leading to their capture by filters. It is also worth mentioning that changing filters and increasing airflow produces a greater effect on the total particle concentration than on the viable particle concentration. This is expected, because viable particles make up only a very small portion of the total particle concentration.

These results are in agreement with those reported by Memarzadeh and Manning (2002) and Vonci et al. (2019). They concluded that increasing air change per hour results in high removal of particles inside an operating room. Chow and Yang (2004) reported that a higher dilution effect leads to a lower concentration of airborne contaminants in operating rooms, including bacteria and anesthetic gas. According to Pereira et al. (2012), indoor particle concentration decreases with increasing air change rate in operating rooms, as indicated by the simulation results.

Although there is presently no common standard method used to determine the microbiological threshold limits in surgical room settings (Dharan and Pittet 2002), the average microbiological particle concentration determined in this study after filter replacement was similar to that previously reported in other studies (Vonci et al., 2019). Landrin et al. (2005) determined a microbiological count ranging from 0 to 38 CFU/m$^3$. Dallolio et al. (2017) monitored 10 operating rooms found a microbiological contamination of air ranging from 2 to 27 CFU/m$^3$.

The results also showed that after filter replacement, the total count of particle concentration agreed with previous studies (Pereira et al., 2012; Nimra et al., 2015). Mirhoseini et al. (2015), using an optical particle counter (0.5–10 µm) to assess the total particle concentration in an operating room and found an average concentration of $0.4 \times 10^6$ particle/m$^3$. Nimra et al. (2015) compared the total concentration of particles in the air in public and private hospitals and found an average concentration of $4.0 \times 10^6$ particles/m$^3$ in public hospitals and $0.1 \times 10^6$ particles/m$^3$ in private hospitals. Morawska et al. (1998) investigated the particle concentration levels and size distribution in a complex hospital system using submicrometer and supermicrometer instrumentation. The authors found a particle concentration (0.5–30 µm) of $0.7 \times 10^6$ particles/m$^3$ in a small surgical room. Regarding the species of microorganisms found inside the room, the results showed a significant prevalence of gram-positive bacteria during most of the surgeries. It was also found that the prevalence of gram-positive bacteria was not affected by filter replacement. This finding was in accordance with Dolinger et al. (2010), who also found a high prevalence of gram-positive bacteria during different orthopedic surgeries. Furthermore, Gallo et al. (2003) suggested that the gram-positive bacteria that are released from skin, hair, and nostrils may be deposited on surfaces. However, according to Edmiston et al. (2005), skin and nasal shedding by members


table 3
gram-negative and gram-positive bacterial percentages, prevalence of coagulase-negative Staphylococci, and concentrations of CO$_2$ measured during all the surgeries

| Case 1 | Case 2 | Case 3 |
|--------|--------|--------|
| %Gram-negative | %Gram-positive | %Gram-negative | %Gram-positive | %Gram-negative | %Gram-positive |
| Average | 9 | 91 | 8 | 92 | 9 | 90 |
| uncertainty | 4 | 4 | 5 | 5 | 6 | 6 |
| Prevalence of coagulase-negative Staphylococci (%) | | | |
| Average | 86 | 67 | 76 |
| uncertainty | 3 | 16 | 9 |
| CO$_2$ concentrations (ppm) | | | |
| Average | 663 | 659 | 576 |
| uncertainty | 21 | 28 | 4 |
of the surgical team might be a risk factor for perioperative contamination and subsequent infection.

Further observation regarding the species of microorganisms revealed that after filter replacement, there was a decrease of 23% in coagulase-negative Staphylococci, which were found to be present during 76.75% of surgeries, while gram-negative bacteria were present in 9.0% of the cases. Edmiston et al. (2005) found that Staphylococci and gram-negative bacteria were present in 86% and 33% of cases, respectively. Coagulase-negative Staphylococci are among the most commonly identified microorganisms in surgical site infections (Edmiston et al. 2005; Becker et al. 2014). According to Dolinger et al. (2010), most orthopedic implant-related infections are due to gram-positive aerobic bacteria, predominantly S. aureus and S. epidermidis (44–50%). These microorganisms form biofilms on the surfaces of prostheses and implants, thereby providing resistance to antibiotics Roberts et al. (2006). Suggested that skin flakes are relatively large particles (4–25 µm) that can transport Staphylococci when released or re-suspended.

Therefore, despite the threats posed by these microorganisms, few studies have comprehensively addressed the transmission route of coagulase-negative Staphylococci in hospitals (Milisavljevic et al. 2005; Monsen et al. 2005; Botelho et al. 2012). According to studies, coagulase-negative Staphylococci have emerged as high-risk pathogens in relation to the development of post-surgical infections, particularly in prostheses surgeries (Dolinger et al. 2010). According to Sagi et al. (2002), instruments that have an air exhaust may be a source of airborne microorganisms, among which the major microorganisms are coagulase-negative Staphylococci and Micrococcus sp.

With respect to CO2, it was found that the concentration was not affected by filter replacement. The CO2 concentrations remained practically constant and below 1000 ppm for all three cases. This is because even with saturated filters, the amount of air supplied to the room is sufficient to dilute the CO2 generated by the people. However, it is not sufficient to dilute the particles generated inside the room.

Finally, it was also found that temperature and humidity were not affected by filter replacement. Both remained constant for all three cases.

Conclusions

The total and viable particle and CO2 concentration in an old operating room before the air conditioning filters were replaced, after the air conditioning filters were replaced, and in a new operating room with a new filter and normal airflow were studied. The results of this exploratory study showed that systems operating with saturated filters can suffer from pressure drop, which can lead to reduced air flow, resulting in an increase in the average of total particle and viable particle concentrations. However, the replacement of the filters does not affect the CO2 concentration.

Few studies have undertaken a quantitative determination of the impact of the filtration system on indoor contamination in an orthopedic operating room. Further studies are needed in this field to ensure good indoor air quality and to protect patients and healthcare workers against hospital-acquired infections and occupational diseases. Therefore, the practical data presented in this work could serve as a basis for corrective action in controlling airborne contamination in operating rooms and may contribute to the overall knowledge of the importance of ventilation and filtration systems in this field.

Finally, it is also important to highlight that the pressure drop in filters is a factor that directly affects the extra electric energy power in the fan operation and may adversely affect the performance of the air conditioning system. Hence, in future studies, it will be important to assess whether the fan motor electric energy consumption savings would cover the costs of replacing the filters.

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Compliance with Ethical Standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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