MODELING AND MEASUREMENT OF AIRBORNE PARTICLE CONCENTRATION IN AN OPERATING ROOM

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Abstract. Particle concentration inside an operating room can vary intensely depending on the type of activity performed inside on the room and the capacity of the air conditioning system in removing it. *In this work spatial and temporal variations of indoor air particle sizes and concentrations were investigated in an operating room. For this, were applied a balance mass model and experimental data. The principles of the model proposed for the simulation of indoor air particle concentrations from different sources and their relative advantages and limitations are then discussed in detail. A statistical comparison of measurements and predictions using the proposed model were performed per ASTM D5157 technical norm. In a general way, it was verified that the proposed model proved to be a good tool for predicting concentrations of indoor air particles. The results showed that as more exacta the information such building and pollutant characteristics and indoor sources are, greater is the accuracy of the proposed mass-balance model. Stands out that the model described here is particularly useful to identify the key building factors that influence indoor concentrations of air pollutants. These models can also estimate the relative importance of different particle sources.*

Keywords*: modeling, airborne particle, operating room, air quality, mass balance models*

1. INTRODUCTION

To prevent infections after surgical operations, airborne particles in the operating room need to be controlled below a certain limit. The dynamic behavior of aerosol particles and their transport indoors can be studied with mathematical models that describe the change rate of aerosol particle concentrations. Mathematical models can be used to quantify relationships between concentrations and important variables, extrapolate from just a few measurements to a large sample, quantify the relative contributions of different pollution sources, estimate indoor concentrations in situations in which measurements are unavailable (Milner et al, 2004).

The concentration of air contaminants as a function of time in an occupied space can be calculated using differential equations obtained by mass balance models. Mass balance models are used to simulate average indoor air pollutant concentrations as a function of outdoor concentrations, building and pollutant characteristics and indoor sources (Milner et al, 2004; Pereira, 2008). These models are widely used due to the simplicity of the mathematics involved and to provide the tools best suited for studying general indoor air quality problems under a wide range of conditions. The development of models can also improve our understanding of indoor air particle dynamics and infection control in operating rooms.

If more is known of the characteristics of the building and sources, these models are extremely useful since they calculate indoor concentrations that may be well compared to experimental data and may be easily linked to exposure models.

In this context, the objective of this work was investigate the variations of concentrations utilizing a balance mass model and experimental data. A statistical comparison of measurements and predictions were performed per ASTM D5157 (2008) technical norm.

2. METHODS

2.1 The room and its HVAC system

In the present study the room has rectangular form with 6.20 x 5.80 x 3.15m, located in São Paulo city. The HVAC system located in a plant room adjacent to the operating room is of type fan-coil. It operated with absolute filtration (HEPA) with 16 ACH (Air Changes per Hour). The ventilation system consists on a single inlet diffuser located at the superior side of the wall with an outlet grille in the opposite inferior side of the same wall. The diffuser supplies an unidirectional jet of air in the environment. The room architecture, the layout of equipment and details of the air supply system are shown in Fig. 1.

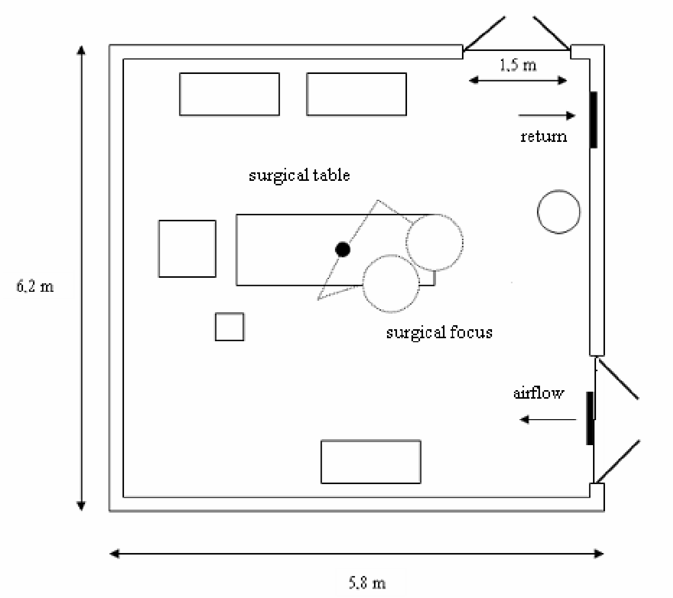

Figure 1. A schema representation of the operating room

2.2 Experimental technique and instrumentation

Indoor and outdoor air particle concentration measurements were obtained simultaneity during the surgery. The concentration and the size of the particles counting was started with an empty theater, soon after the cleansing process and before the patient's entrance, and continued until the patient left the theater. There was a 5-minute interval between each collection and the sampling time was 1 minute.

Particle concentrations were measured with a particle counts with six size ranges, 0.3 µm to 0.5 µm, 0.5 µm to 1.0 µm, 1.0 µm to 3.0 µm, 3.0 µm to 5.0 µm, 5.0 µm to 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).

2.3 Modeling technique

In this study the mass balance model is used to simulate average indoor air particle concentrations as a function of HVAC, building and particle characteristics and indoor sources.

To get the basic equation, it was made a balance of particles, i.e., the total number of particles indoors is equal to the sum of particles introduced from outside and generated by indoor sources less particles removed by the HVAC system and by deposition on the surface (Jamriska et al., 2000; Pereira, 2008). The model assume the hypotheses of perfect mixing, i.e. a uniform concentration of contaminants in the whole volume (Nazaroff and Cass, 1989).

In a general way, the basic equation represents the variation of the indoor concentration, in the room volume, over the time. Based on the above assumptions and utilizing the mass balance conception, the variation in particle concentration can be given by:

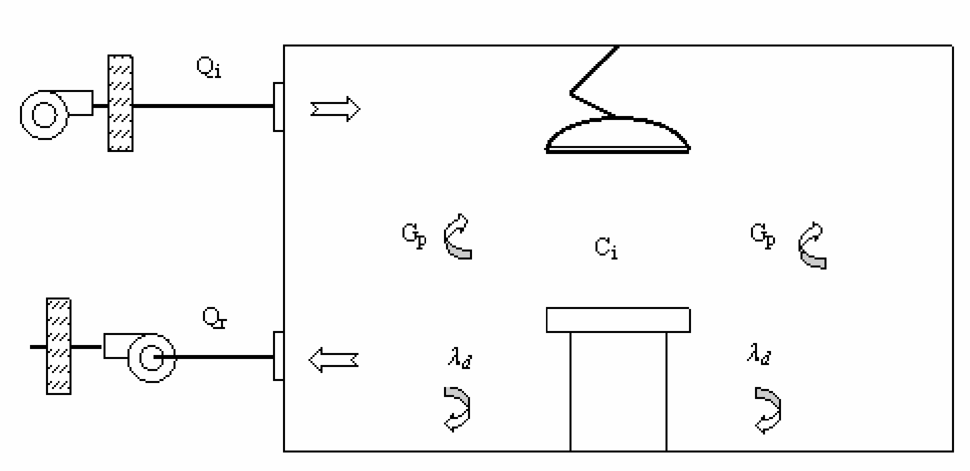

Figure 2. Variation of the indoor in the room volume

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

C_i = indoor particle concentration at time t ; C_o = outdoor particle concentration; V = volume of the space; G_p = particle generation rate; C_o = particle from the outdoor air; Q_s = airflow from supply air into the room; Q_r = airflow from the room to the outdoor air; η = removal efficiency of the HVAC filter; λ_d = particle deposition rate.

The positive terms are the emissions source in the room and the negative terms are the different removal process from indoor air. Solving equation 1 above provides the general equation solution in equation 1, written as:

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

where Ci = initial concentration of particles in the space.

As can be seen, the mathematical model developed by means of this method requires a set of input parameters, such as the initial indoor characteristics, filtration, ventilation, particle deposition rate, etc. The initial particle concentration measured outside at the beginning of the modeled time period was used as the initial concentration (C_0). The airflows of outside and return air were considered to be equal. The filtration efficiency parameter was assessed as the overall reduction in particle concentration in the Air-Handling Unit (AHU) caused by the filters and the air-conditioning process (Jamariska et al., 2000).

The deposition rate utilized in this study is based on results from experimental studies (1-3). These studies measured the indoor deposition loss rate over a range of particle sizes, ventilation conditions, and indoor surface area to volume ratios.

Addition the particles from HVAC, in this study, the presence of people and their activity indoors were considered another 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 (Salvigni et al., 1996, Jamariska et al., 2000). It was considered a team with four people.

Also, in the development of this model it was considered that densities of return and outlet air are same, that contaminant is generated continuously at steady rate, and that infiltration or leakage occurs.

2.4 Statistical evaluation

The results from the model were compared with experimental results based on ASTM guide D5157-2008 Standard Guide for Statistical Evaluation of Indoor Air Quality Models (ASTM 2008). This standard provides quantitative and qualitative tools for evaluation of indoor air quality (IAQ) models. Also provides information about statistical tools for assessing model performance. The standard gives three statistical metrics for assessing accuracy and two additional metrics for assessing bias.

In this article were used the following tools for assessing agreement between predictions and measurements:

1) The correlation coefficient of predictions and measurements should be 0.9 or greater. The correlation coefficient is calculated as:

$$r = \frac{\sum_{i=1}^{n} [(C_{0i} - \overline{C}_0)(C_{pi} - \overline{C}_p)]}{\sqrt{\sum_{i=1}^{n} [(C_{0i} - \overline{C}_0)^2][\sum_{i=1}^{n} (C_{pi} - \overline{C}_p)^2]}} \tag{3}$$

2) The line of regression between the predictions and measurements should have a slope between 0.75 and 1.25 and an intercept less than 25 % of the average measured concentration.

3) The normalized mean square error (NMSE) should be less than 0.25. The NMSE is calculated as:

$$NMSE = \frac{\sum_{i=1}^{n} (C_{pi} - C_{0i})^2}{2\overline{C}_0 \cdot \overline{C}_p} \tag{4}$$

where C_p is the predicted concentration and C_o is the observed concentration, and the over-bar represents an average over the n data points during the test period for each test case.

3. RESULTS

Figure 3 shows the variation of the particle concentration during a surgery. As can be seen in Figure 3, initially, with the empty room the particle concentration suspended in the air is relatively low. In the preparation for surgery, with the entry of the patient and the surgery team, particle concentration increases. The peak on particle concentration during preparation for surgery occurs principally due to the placement of the gowns and surgical linen. During surgery, the particle concentration also decreases. At the end of surgery, there is another peak because of the withdrawal of the surgical linen and the removing of the patient from the room.

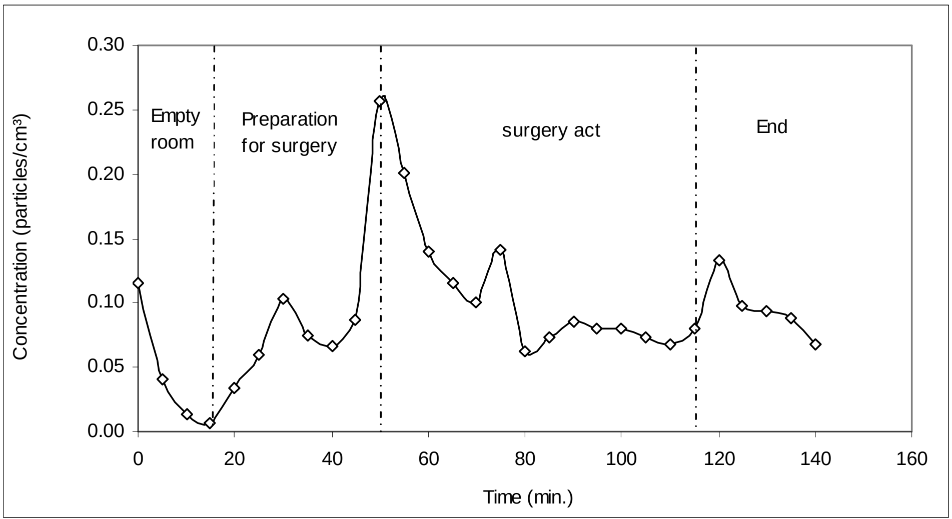

Figure 3. Particle concentration during surgery

Figure 4 shows a comparison between the concentrations of particle measurements inside the room and the concentrations predicted by the model.

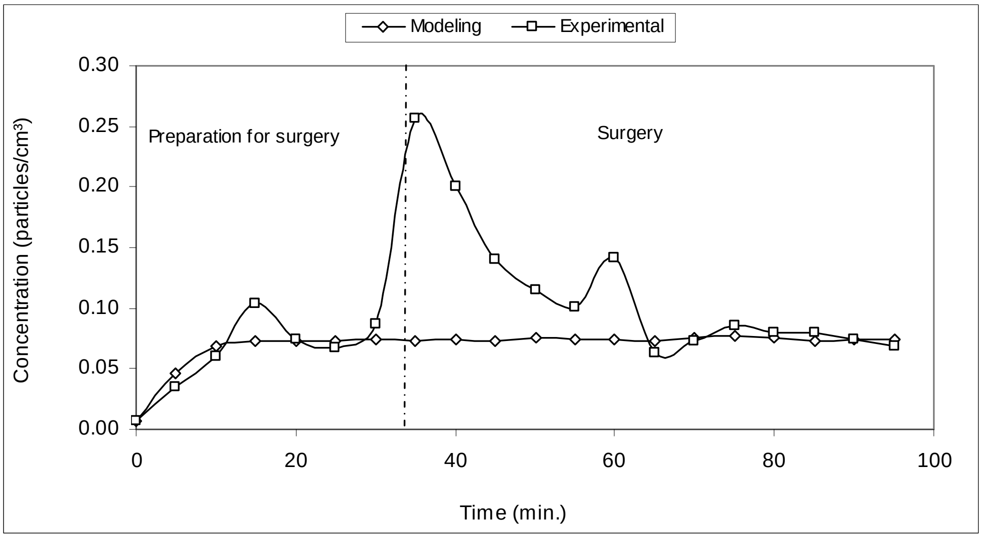

Figure 4. Comparison between experimental data and model

Figure 5 presents a comparison between the measurements particle concentrations inside the room and the concentrations predicted by the model, without considering the particles generated in the placement of the gowns and surgical linen.

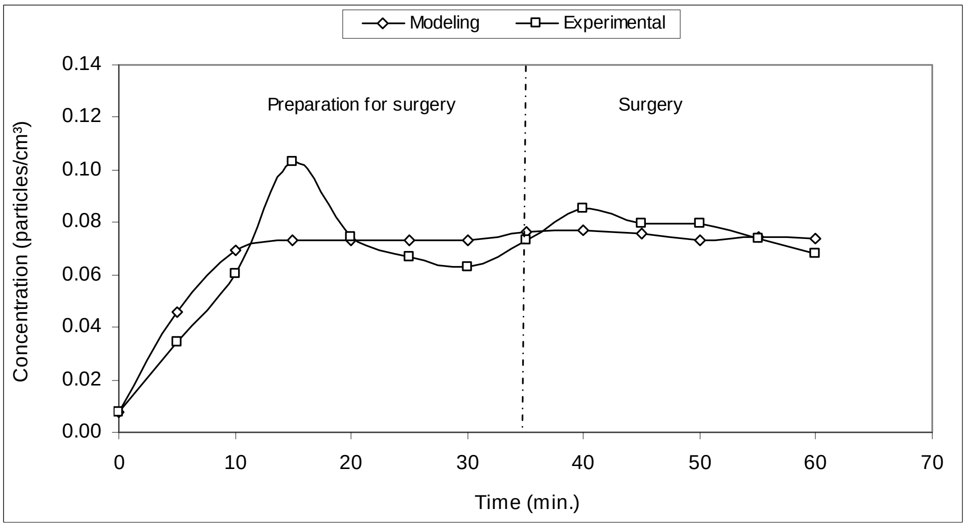

Figure 5. Comparison between experimental data and model: with the purge of data

In the case of figure 6, there is a comparison between the concentrations of particle measurements inside the room and the concentrations predicted by the model, assuming multiply a correction factor that takes into account the effect of particles generated by the placement of gowns and surgical linen.

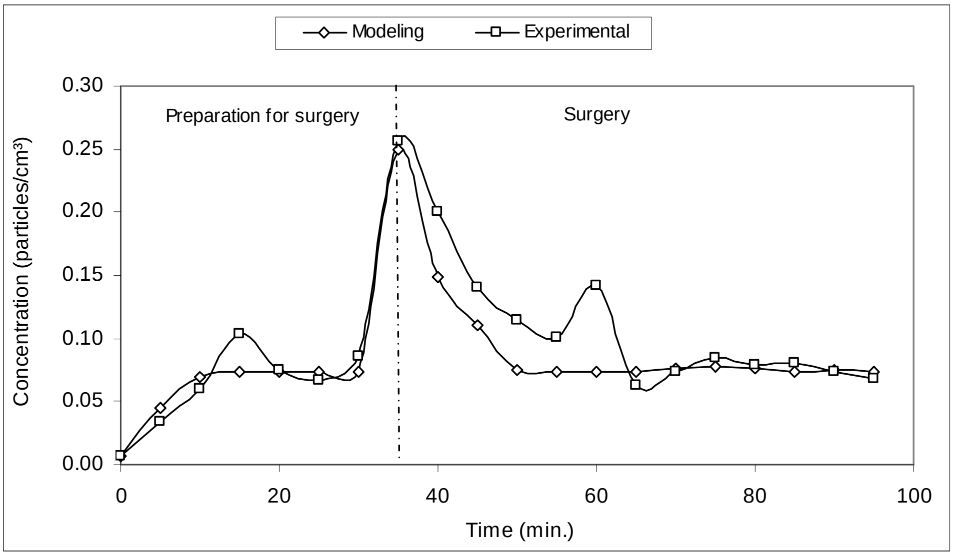

Figure 6. Comparison between experimental data and model: with a correction factor

4. ANALYSIS OF RESULTS

4.1 Particle concentration over time

The experimental results showed that particle concentration varies with time. With the empty room the particle concentration suspended in the air was relatively low. In the preparation for surgery, the number of occupants in the room rises and, consequently, the particle concentration increases. The peak on particle concentration during preparation for surgery occurs principally due to the placement of the gowns and surgical linen. The high activity level during of the surgery team also contributed with particle generation. There is an elevated release of cotton fibers particles and skin particles into the environment.

During surgery, the activity level inside the room reduces and therefore the particle concentration also decreases. In this stage there is a reduction in the amount of particles released from the body and there is not movement of the gowns and surgical linen. It is important to highlight that action of the air conditioning system and the deposition process also influence in the particle reduction.

At the end of surgery, there is another peak because of the withdrawal of the surgical linen and the removing of the patient from the room.

4.2 Prediction of the particle concentration

The discrepancies between the measurements particle concentrations inside the room and the concentrations predicted by the model can be easily justified. Initially, one might say that in the model was considered as source of particle generation the surgical team and the air conditioning system. But, there are others factors that affect in the particle generation inside of room, for example, the placement and withdrawal of the gowns and surgical linen. This becomes clear when the particles generated by the placement of surgical linen and gowns are purged of the experimental data and compared with numerical data, the proposed model fits better with the experimental data. As well, when is used in the model the correction factor to consider particles generated by these events, the model becomes even more precise.

Another factor that may be producing these differences comes from the fact that there are some factors that the model was considered the generation of particles in the environment was continuous, with the same number of people inside the operating room. But, it is not occur in practice, because depending on the different activities taking place in the room and also varying the number of people the particle concentration varies with time.

Moreover, in the model is estimated that the amount of particles released from a person inside the room is about 14,000,000 particles per hour. This value is suggested in the literature, but in an operating room, the type of clothing used and activity level influence the amount of particles scattered by a person. So the amount suggested in the literature may be quite different from the actual amount generated inside the room.

The Table 1 show a compared between experimental result and modeling result based on ASTM guide D5157-2008 Standard. It can be seen that when is compared the whole experimental and modeling data, it is attended partiality (r = 0,4618; NMSE = 0,1280) the criterions established by the standard. When there is purge from the experimental data the parameters that aren't considered in the model the data attended (r = 0,8920; NMSE = 0,0243) the criterions established by the standard. As well when is used a correction factor both criterions (r = 0,9072; NMSE = 0,1137) are attended.

Tabela 2. Assessing model performance

	Criterions	
	r	**NMSE**
- Total data	0.4618	0.1280
- With purged data	0.8920	0.0243
- With correction factor	0.9072	0.1137

5. CONCLUSIONS

The main objective of this study was to develop a mathematical model as a function of HVAC concentrations, building and particle characteristics and indoor sources to predict the particle concentration in operating rooms. The results showed that the analysis of the variation of particle concentrations over time is important to determine which factors are dominant in the generation and removal of particles and during which times and what activities would occur more or less particle generation.

The data sets collected during this study meet the ASTM D5157-2008 criteria for model evaluation. Also, the results showed that the proposed model proved to be a good tool for predicting concentrations of indoor air particles. That is, it was found that when there aren't large variations the proposed model can predict with accuracy the particle concentration within the operating room over time. As more exacta the information such building and pollutant characteristics and indoor sources more is the accuracy of mass-balance models.

The major limitation of mass-balance modeling approaches is the assumption that a spatially uniform concentration in the whole operating room. Surgical activities changed frequently, different tools are used and surgeons or nurses change locations within the room time to time. Due to this changing nature, the particle concentration and size can vary widely from procedure to procedure from time to time during the same procedure. Then the results obtained in this work can not represent the behavior of particles in the whole room.

In general, results in this study could provide valuable information to the facility engineer facing the high particle counts in the operation room for infection control. Also, can contribute to overall knowledge about the existing relationship between the particles generated and the activities performed in operating rooms.

Although in study the model user simulated with precision the particle concentration within the operating room over time, further studies with different methodologies such as the technique of Computational fluid dynamics (CFD) simulation are needed to provide information such as the room air movement and to confirm infection risk.

ACKNOWLEDGEMENTS

Victor Barbosa Felix, Marcelo Luiz Pereira and Arlindo Tribess wish to acknowledge CNPq for the financial support received.

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