ASSESSMENT OF VENTILATION RATES USING METABOLIC CO_2 CONCENTRATIONS IN A SURGICAL ROOM CONDITIONED WITH A WINDOW/WALL AIR-CONDITIONING SYSTEM

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Abstract. *For air-conditioning systems design, a medical facility can be considered to contain six general areas including Critical, Sensitive, Clinic, Administrative, Support areas, and Patient Bedroom areas. Then, different type of air-conditioning systems and air flow pattern are used not only to maintain minimum requirements of comfort and ventilation, but also for the control of infection, removal of noxious odors, dilution and expelling of contaminants, and establishment of special environmental conditions conducive to medical procedures and patient healing. The type of system employed will have a significant influence on air flow patterns within the building and can have a significant impact on the indoor air quality. On account of easy handling and installation, as well as economic considerations, window/wall air-conditioning systems are used in many surgical rooms. Therefore, the objective of this study is to assess ventilation rates (outdoor air ventilation (cfm)), using metabolic CO_2 as a natural tracer gas, in a surgical room conditioned with a window/wall air-conditioning system. CO_2 concentration and occupancy were monitored in the room during surgical procedure. Ventilation rate provided by the window/wall air-conditioning system was estimated, based on CO_2 generation, CO_2 measured and room occupancy. Ventilation rate required to maintain the indoor CO_2 concentration within acceptable levels (1000 ppm) was calculated, and then compared with the real ventilation rate provided by the window/wall air-conditioning system. The results showed that CO_2 concentration increased continually during the whole surgical procedure, reaching approximately 3000 ppm (1000 ppm recommended by standards). These values represent that almost three times less outdoor ventilation was provided by the system than was necessary to maintain good indoor air quality. Consequently, the ventilation rate required, in order to maintain acceptable CO_2 levels, was higher than provided by the window/wall system, especially when the room occupancy increased. This suggests that window/wall air-conditioning systems are not suitable for use in surgical rooms due to their insufficient renovation with outdoor air.*

Keywords*: aerial contamination, surgical room, air conditioning system, infection, ventilation.*

1. INTRODUCTION

Ventilation is the process of supplying or removing air to or from any space, by natural or mechanical means (ASHRAE 2013). The general purpose of ventilation in buildings is to provide healthy air for breathing by both diluting the pollutants originating in the building and removing the pollutants from it (Etheridge & Sandberg, 1996; Awbi, 2003; Li et al. 2007). According to Li et al. (2007) there is strong and sufficient evidence to demonstrate the association between ventilation and the control of airflow directions in buildings and the transmission and spread of infectious diseases (Li et al. 2007). Thus, it may be said that, the ventilation is possibly the most powerful tool that is available when attempting to control the indoor environment in a health care facility. By adding uncontaminated air into the space, contaminants can be removed or concentrations reduced to acceptable levels within the space. However, just as a properly designed ventilation system can act as a powerful control, an improperly designed ventilation system act as a potential hazard. In fact, an improperly designed ventilation system may be more dangerous than no ventilation system at all, because of the false sense of security that the presence of such a system gives to the occupants (Talty 1989).

Unfortunately, on account of their low price, simple installation, operation and maintenance, Window/Wall Type Air-conditioning or Split Systems have largely been used in operating rooms , notedly in Brazil. Normally, these types of systems only recirculate the air inside the room without appropriate filtration and renovation with outdoor air. Besides, this kind of equipment produces horizontal jet flow and a large amount of turbulence in the room in contrast with the conventional downward flows system (Karthikeyan and Samuel, 2008; Pereira et al., 2009). Moreover, due to the way that this equipment moves the air inside of the room, the surgical wound, people and surgical equipment are not protected against air contamination liberated at different points in the room. In the same way, it interferes with the pressure of the surgical room, and consequently with the maintenance of the pattern airflow between the rooms of the surgical center, allowing pathogenic agents to come through other section entrances into the surgical room (Pereira, 2008). It is also important to highlight that, although Window/Wall Air-conditioning and Split Systems are often used, there are few published studies that examine the impact of these types of equipment on indoor concentration and distribution of contamination in operating rooms (Karthikeyan and Samuel, 2008; Pereira et al., 2009).

The measurement of CO_2 levels can indicate the amount of outdoor air that enters a building (Spagnoli et al, 1996). High indoor CO_2 levels indicate that the building is not receiving the sufficient ventilation required to dilute the indoor contaminants (Karthikeyan and Samuel 2008; Spagnoli et al 1996; ASHRAE 2010; Persily 1996). Adequate ventilation is needed to dilute indoor contaminants and to control the build up of these contaminants (Pereira et al., 2009). To provide a healthy environment for the building occupants the indoor CO_2 level should stay within 700 ppm of the outdoor level.

Usually the level of CO_2 in outdoor air is approximately 350 ppm. The release of CO_2 by occupants during the respiration processes causes indoor CO_2 concentrations to exceed outdoor concentrations. The amount depends on the rate of outside air supply per occupant and the time elapsed since the occupants entered the building. Concentrations of other indoor-generated contaminants can be correlated with the concentration of the CO_2 in indoor environments. This correlation should be higher for other human bioeffluents and weaker for pollutants emitted by building materials, furniture, electronic and office equipment, cleaning and other activities (ASTM D6245-2007).

In this context, this study aimed to assess ventilation rates, using metabolic CO_2 as a natural tracer gas, in a surgical room conditioned with a window/wall air-conditioning system. CO_2 concentration and occupancy were monitored and the current ventilation rate per person effectively delivered to the room was estimated comparing the CO_2 generated by the occupants with CO_2 levels measured inside the room. Outdoor air ventilation (L/s) required to maintain the indoor CO_2 concentration within acceptable levels (1000 ppm) was calculated, and then compared with the real outdoor air ventilation provided by the window/wall air-conditioning system.

2. MATERIALS AND METHODS

2.1 Determination of Ventilation Rates

People produce and exhale CO_2 as a consequence of their normal metabolic processes; thus, the concentrations of CO_2 inside occupied buildings are higher than the concentrations of CO_2 in the outdoor air. Indoor CO_2 concentration is strictly dependent on the number of people in a building, and the efficiency of the ventilation system in diluting occupant generated CO_2.

CO_2 measurement can be useful in efforts to assess the effective delivery of outdoor ventilation air into the occupied space. On this base, the current ventilation rate per person effectively delivered to the space, on a per-person basis, can be calculated by the CO_2 generation rate of the occupants and differential between indoor and outdoor CO_2 concentrations (Hellickson and Walker, 1983; CIGR, 2002; Rudnick and Milton, 2003; ASTM D6245-2007; ASHRAE 62-2010, Samer and Abuarab, 2014). The follows equation explains the relationship between the CO_2 generation rate of the occupants and indoor CO_2 concentrations, assuming ideal mixing with the air inside the room:

$$Q = G/(Ci - Co) \qquad (1)$$

Where:

G = CO_2 generation rate per person;
Ci = CO_2 concentration indoors;
Co = CO_2 concentration outdoors;
Q = outdoor airflow rate per person.

If the generation rate (G) and the outdoor airflow rate per person (Q) are expressed in L/s, and the concentrations are in mg/m^3, then Equation (1) takes the form:

$$Q = 1.8 \text{x} 10^6 \, G/(Ci - Co) \qquad (2)$$

Human metabolism consumes oxygen (V_{O2}) and generates CO_2 (Vco_2) at rates that depend on the level of physical activity, body size, and diet. Thus, the equation (2) can be written in terms of Vco_2:

$$Q = 1.8 \text{x} 10^6 \, Vco_2/(Ci - Co) \qquad (3)$$

The CO_2 generation rate of an individual is equal to VO_2 multiplied by the respiratory quotient (RQ). The respiratory quotient is the ratio of the volumetric rate at which CO_2 is produced to the rate at which oxygen is consumed.

The respiratory quotient (RQ) is the volumetric ratio of carbon dioxide produced to oxygen consumed. It varies from

0.71 for a diet of 100% fat to 0.8 for a diet of 100% protein and 1.00 for a diet of 100% carbohydrates (see Reference C-l). A value of RQ = 0.83 applies to a normal diet mix of fat, carbohydrate, and protein. (ASTM D6245-07 2007, ASHRAE, 2013). Thus, the generation of CO_2 (V_{CO2}) in L/s of a person is given by:

$$V_{CO2} = RQ \cdot V_{O2} \tag{4}$$

Based on ASHRAE (2013), the rate of oxygen consumption in L/s of a person is given by:

$$V_{O2} = (0.00276\ A_D\ M)/(0.23\ RQ + 0.77) \tag{5}$$

Where;

A_D = Dubois body surface area, m2;
RQ = respiration quotient (ratio of CO_2 exhaled to O_2 inhaled);
M = metabolic rate per unit of surface area, met (1 met = 58.2 W/m^2);

The DuBois surface area of a nude body, can be estimated by the following equation (ASHRAE, 2013):

$$A_D = 0.203 H^{0.725} W^{0.425} \tag{6}$$

Where;

H = is the body height in m;
W = is the body mass in kg.

2.2 Measurement localization

The measurements were carried out in an operating room with an area of approximately 28 m^2, in an old hospital for treatment of infectious diseases. The surgical center of the said hospital has just one surgical room. This surgical room has a Window/wall type of air conditioning system with a capacity of 18,000 Btu/h. Figure 1 shows the surgical room with the Window/wall air conditioning system in which the measurements were taken.

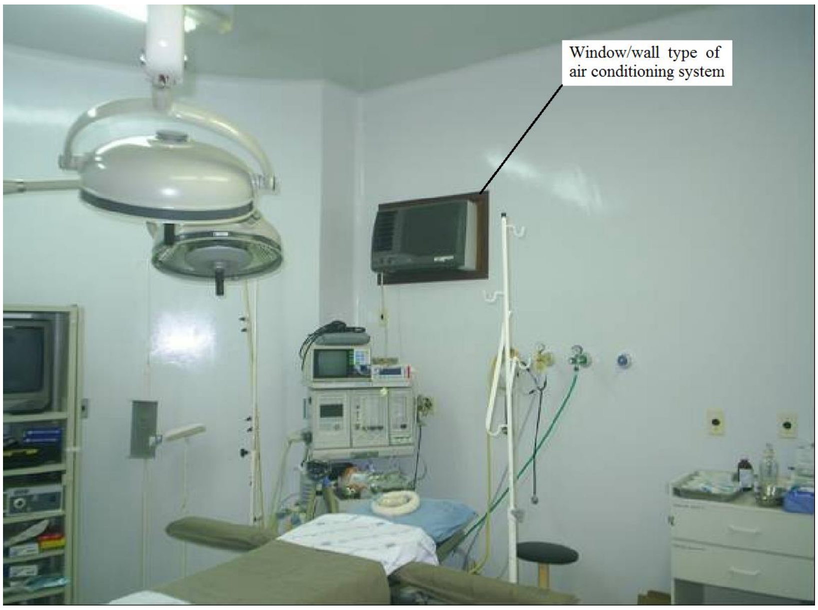

Figure 1 – View of the surgical room and air conditioning system.

2.3 Instrumentation

In the surgical room the CO_2 concentration levels were obtained through direct monitoring, in real time. During the measurements the sensors were positioned away from any source that could directly influence the reading.

For the surgery analyzed, the measurements and recording of activities began before the patient entered the room, right after the cleaning of the room while it was still empty, and finished soon after the departure of the patient. The activities performed in the operating room were also recorded at 5-min intervals.

2.4 Parameters for the calculation of the CO_2 generated per person

In this study a comparison was made between the outdoor air requirements for ventilation in L/s necessary to maintain indoor CO_2 concentration within acceptable levels (1000 PPM) at all times with the real outdoor air ventilation provided by the ventilation system. Following this an estimate of the outdoor air ventilation requirements based on CO_2 generation was determined using the equation (3) which was considered the number of people in the space, the rate of CO_2 generated per person, VC_{O2} (G), calculated by equation (4), CO_2 concentration indoors (measured) and CO_2 concentration outdoors (400 ppm). Table 1 presents the values considered for calculation of the rate of CO_2 generated per person, VC_{O2}.

Table 1. Parameters for the calculation of the CO_2 generated per person, VC_{O2}.

Parameter	Value
A_D (m^2)	2
RQ	1
M (58.2 W/m^2)	232,8

3. RESULTS

Figure 2 shows the CO_2 concentration and number of people inside the room. It can be seen that CO_2 concentration, was already 1000 ppm before the patient entered the room. This increased progressively during the start of activity reaching approximately 3000 ppm by the end of the surgery.

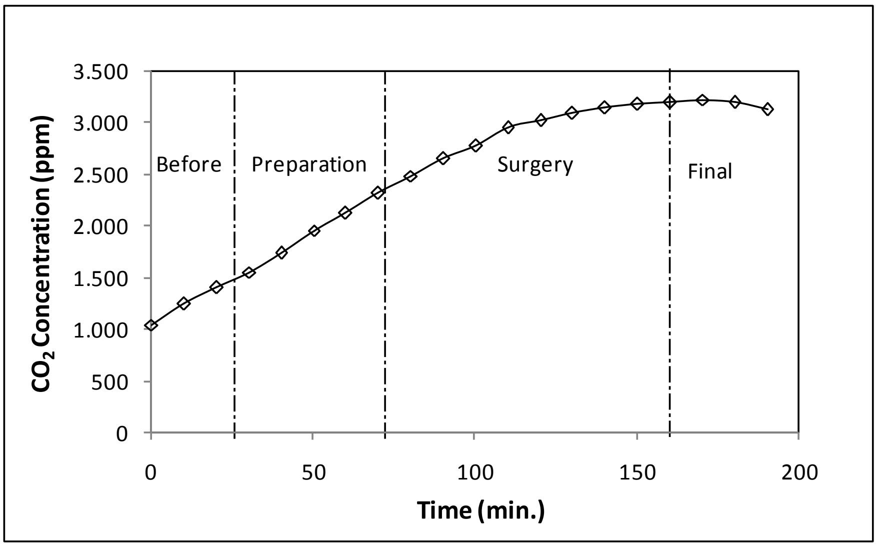

Figure 2 - CO_2 concentration inside the room.

Figure 2 shows the variation in the number of people in the room during the different surgical procedural steps. Initially the number of people was 2, which gradually increased during preparation time, arriving at 6 before the surgery began. During the surgery this value stayed at 6 for the majority of the time. Towards the end of the surgery, the number of people fell to 3.

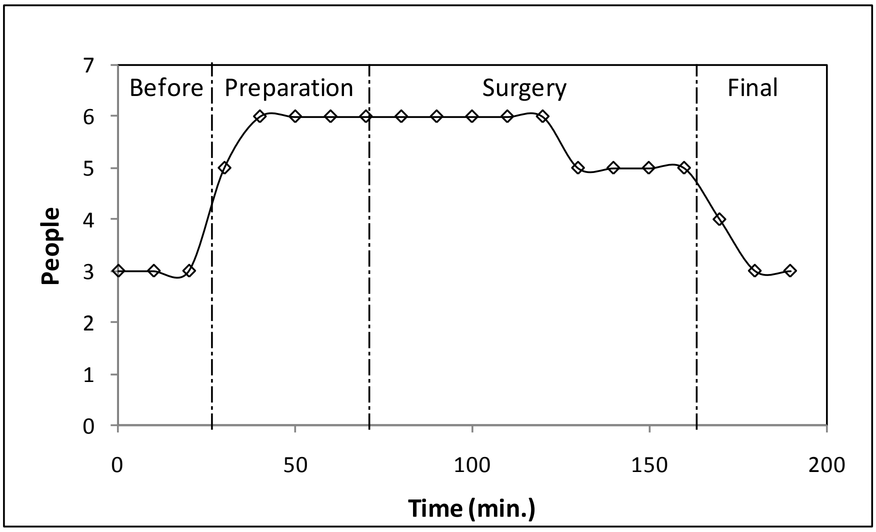

Figure 2 - Number of people inside the room.

Figure 4 demonstrates a comparison between the outdoor air requirements for ventilation in L/s necessary to maintain the indoor CO_2 concentration within acceptable levels (1000 ppm), and the real outdoor air ventilation provided by the ventilation system. It can be seen that, at all times, the outdoor air requirements were greater than the real outdoor air ventilation provided by the air conditioning system. This was especially at the end of preparation for surgery and most of the time during the surgery when the number of people increased. For example, during the surgery the average of outdoor air requirements were 181 cfm, while the real outdoor air ventilation provided by the air conditioning system was measured as only 54 cfm. These values represent that almost three times less outdoor ventilation was provided by the system than was necessary to maintain good indoor air quality.

It can also be noticed that even before the patient entered, at which point the number of people was small, the outdoor air ventilation provided by the system was not able to obtain acceptable indoor air quality.

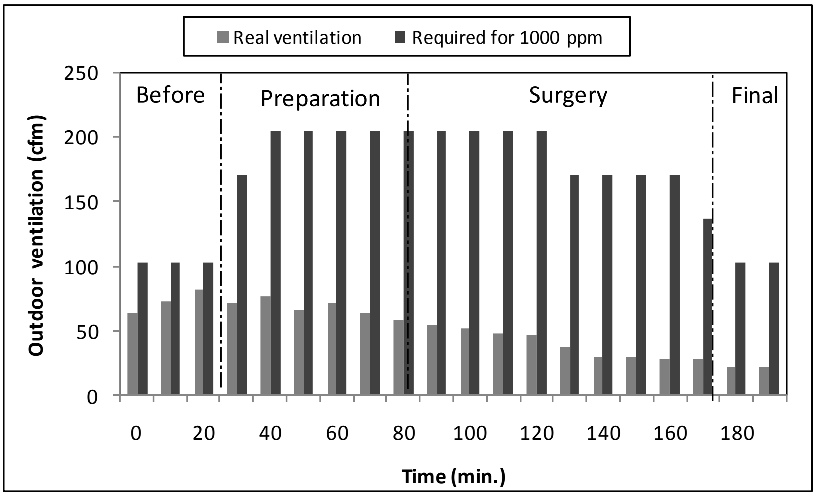

Figure 4 – Comparison between the real outdoor air ventilation provided by the air conditioning system and the required amount to maintain a concentration of 1000 ppm.

4. DISCUSSIONS

4.1 Estimative of actual ventilation ratio using metabolic CO_2

The actual ventilation ratio being effectively delivered to the room was estimated comparing metabolic CO_2 concentrations and production rates inside the gyms center. CO_2 can act as an indicator of ventilation efficiency, showing whether the supply of outside air is sufficient to dilute air contaminants (You et al., 2007).

Some limitations of this approach include: requirement for uniform concentration of CO_2 throughout the space analyzed, steady-state conditions or equilibrium concentration, accuracy of measurement, representative sampling location, and accurate occupancy information.

Regarding these limitations, it is important to discuss two of them: the requirement for uniform concentration of CO_2 and equilibrium concentration. Steady-state conditions or equilibrium concentration, meaning that the indoor CO_2 generation rate, the outdoor CO_2 concentration and the outdoor airflow rate are constant for a sufficient long period of time such that the indoor concentration stabilizes to a constant value. According to Persily (1989, 1997), the assumption of equilibrium conditions for estimating ventilation rates using CO_2 concentration may not be valid, because this condition is difficultly achieved. The time required to reach equilibrium state depends mainly on air change rate. For example, in an 80 m^3 space and the outside and initial CO_2 concentrations are 400 ppm, it takes around three hours to reach 95% of the equilibrium in the CO_2 concentration in a ventilation rate of 0.75 ach and CO_2 generation rate of 0.0052 L/s (approximately one person's CO_2 generation rate in office work) (You et al., 2007).

In the case of fitness centers, where the generation rate of CO_2 and the room volume are high and the occupation is variable, the time required to reach equilibrium can never be achieved. Then, to avoid these problems, an alternative is to consider the average of occupation and CO_2 generation rate at regular intervals.

Regarding the requirement for uniform concentration of CO_2, in the case of the measurements carried out for a long time and where the sources are relatively spread out within the room, the CO_2 concentration over time tends to be uniformly distributed throughout the room. Furthermore, the ventilation system has a greater impact on the air distribution inside the rooms. According to Rim and Novoselac (2008), the indoor airflow pattern mainly depends on the mechanical operation of the fan. That is, during fan operation, forced convection often dominates over the buoyant airflow generated by indoor heat sources, which creates a mixing flow regime in the space (Rim and Novoselac, 2008). In the case of the present work, the air conditioning system remained switched on for all measurements.

Another aspect that should be considered is the measurement in only one point. Although, some works suggest that in some cases it cannot represent the CO_2 concentration in the whole room (Persily et al., 1994; Mahyuddin and Awbi, 2012), this approach is commonly used (Willers et al. 2006; Fromme et al. 2007; Weichenthal et al. 2008; Chan et al. 2009). Fox et al. concluded that a single monitoring location was appropriate for characterizing indoor contaminants levels only when HVAC systems were on, i.e. air was being well mixed. According to Gadgil et al. (2003), for experimental purposes, the measurement of the concentration at only one point can be used to obtain the overall concentration throughout the room.

4.2 The impact of the ventilation system on outdoor air

Various methods of mechanical ventilation and room air distribution have been implemented and used in different types of buildings.

Indoor air quality and thermal conditions can be greatly affected by the type of air distribution system adopted. Airflow patterns and the extent to which supply air mixes with room air are further affected by operating conditions, how the system is used and the location and type of supply outlets and return inlets. Each of these factors can interfere with temperature distributions, contaminant removal and the age of air in the occupied zone, therefore affecting occupant responses to the office environment (Pereira et al., 2009).

Given the importance of ventilation rates in determining indoor contaminant concentrations, it is disconcerting how few published studies that examine the impact of these types of equipment on indoor concentration and distribution of contamination in operating rooms.

Unfortunately, on account of their low price, simple installation, operation and maintenance, window/wall air-conditioning system have largely been used in operating rooms. Normally, these types of systems only recirculate the air inside the room without appropriate filtration and renovation with outdoor air. This allows contaminated air to accumulate inside, causing pollutant concentrations to increase. Besides, this kind of equipment produces horizontal jet flow and a large amount of turbulence in the room in contrast with the conventional downward flows system (Karthikeyan and Samuel, 2008; Pereira et al., 2009).

During the surgery the average of ventilation rate provides by the window/wall air-conditioning system was 54 cfm while the average of outdoor air requirements were 181 cfm. The results obtained in this work show the notable characteristics of this type of equipment, that is a lack of air exchange with outdoor air.

5. CONCLUSIONS

This study aimed to assess ventilation rates, using metabolic CO_2 as a natural tracer gas, in a surgical room conditioned with a window/wall air-conditioning system.The results showed that due to the lack of air filtration and renovation with outdoor air, there is a continuous increase in the concentration of CO_2 during the whole surgical procedure, reaching concentrations above the 1000 ppm, which is beyond the limit recommended by standards (ASHRAE, 2010). This is a characteristic of the window air conditioning system, which does not renew the air inside the room with outdoor air. I.e, temporal patterns seen in the data, suggests that the window/wall air-conditioning system is not appropriate for use in operating rooms because it does not provide adequate removal of contamination generated within the room.

This is a dangerous situation, as a relationship can be established between the CO_2 production and other contaminants generated within an operating room, especially anesthetic gases. According to Spagnoli et al. (1996), the CO_2 concentration normally follows the same tendency as other gases such as anesthetic gases. Thus, the results suggest that the concentration of anesthetic gases inside the room would tend to be high. It is also important to note that exposure to high concentrations of anesthetic gases - even for a short time - can cause adverse health effects. Studies have linked genetic damage of the surgical team, to exposure to anesthetic gases in operating rooms (Hoerauf, 1999). Furthermore, CO_2 levels as found in this work, suggest inadequate ventilation and may lead to higher risk of surgical site infections due to high concentrations and long residence time of airborne contaminants in the surgery room.

Finally, the approach used in this work, is a reliable, simple, fast, and inexpensive method to estimate the ventilation rates. This method offers a viable alternative or supplemental check for quantifying building ventilation rates under conditions where direct, continuous ventilation rate measurement is not feasible. However, the method proposed has several sources of error, such as the calculation of metabolic CO_2 generation.

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