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Increased CO₂ levels in the operating room correlate with the number of healthcare workers present: an imperative for intentional crowd control

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Abstract

The air in an operating room becomes more contaminated as the occupancy of the room increases. Individuals residing in a room can potentially emit infectious agents. In order to inhibit and better understand the epidemiology of surgical site infections, it is important to develop procedures to track room occupancy level and respiration. Exhaled CO₂ provides a respiratory byproduct that can be tracked with IR light and is associated with human occupancy. Exhaled CO₂ can also be used as an indirect measure of the potential release and level of infectious airborne agents. We show that non-dispersive infrared CO₂ sensors can be used to detect CO₂ in operating room air flow conditions of 20 air changes per hour and a positive pressure of 0.03 in. H₂O. The CO₂ concentration increased consecutively for occupation levels of one to four individuals, from approximately 65 ppm above the background level when one individual occupied the operating room for twenty minutes to approximately 300 ppm above the background when four individuals were present for twenty minutes. The amount of CO₂ detected increases as the number of occupants increase, the activity level increases, the residency time increases and when the ventilation level is reduced.

Keywords: CO₂, Operating room, Surgical Site infection, Air Quality, Indoor air, Monitoring

Introduction

In-door air quality is affected by a variety of factors including human occupation [1–3]. Developing and applying effective and non-invasive methods that monitor the amount of people in a room is particularly important in clinical settings where air quality is a major factor that can contribute to nosocomial infection including surgical site infections [4, 5]. It has been reported that 2.0–2.4% of all total joint arthroplasties in the U.S. result in periprosthetic infection [6], which imposes significant morbidity on patients and large financial burdens on the healthcare system [7], making the pursuit of improved air

quality in operating rooms of high importance. In general, the quality of the air in an operating room (OR) will be compromised by various viable and non-viable particulate matter and small molecules as the number of people in the room increases [8]. For example, bioaerosols are emitted into the surrounding environment as people breathe, talk, laugh, cough or sneeze [9]. Additionally, human skin sheds squamous epithelial cells which can contain micro-organisms [10]. A promising strategy for enhancing OR environment management involves the application of automated sensors to track the flow of human traffic and respiration over time. It is well-known that occupants contribute to the concentration of indoor CO₂ [11–13]. Carbon dioxide (CO₂) provides a detectable marker of respiration that can be routinely monitored and is expected to increase in concentration in an indoor

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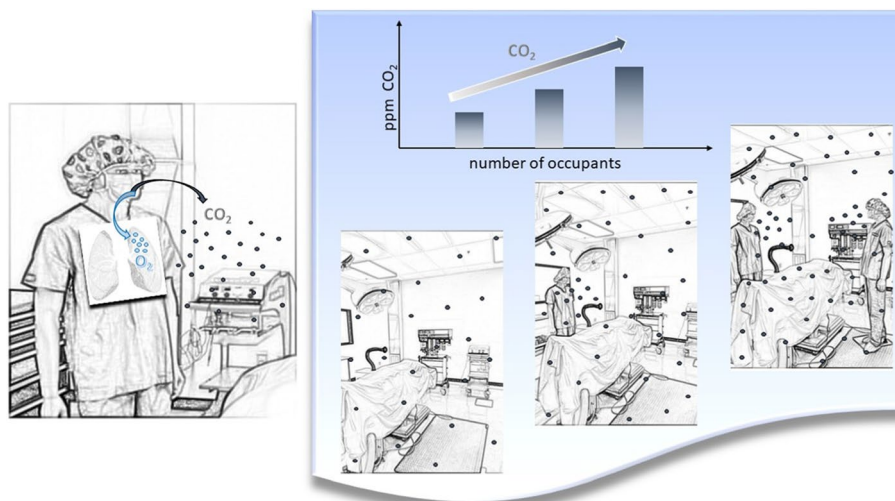


Fig. 1 Exhalation produces CO₂. CO₂ accumulates in the air of an occupied operating room. As more individuals populate the room, the rate of CO₂ accumulation in the room increases

environment as more individuals occupy a room or building (Fig. 1). CO₂ emissions from individuals under various activity levels and environmental conditions is an active area of research. Recent studies have investigated the effect of various conditions including sedentary vs active behavior, indoor pollutants, ambient CO₂ levels, stressed vs relaxed cognitive activities, metabolic rate, temperature, gender and age [14–21]. Measurement of CO₂ concentration has previously been suggested as a tool for estimating airborne infection transmission risk [22]. Recently, analytical expressions were derived for the probability of Covid-19 infection based on CO₂ levels in a number of indoor environments [23]. However, little data is available on the behavior and detectability of occupant-driven CO₂ levels in the operating room environment.

CO₂ exists in a gaseous state under ambient conditions and is a by-product of respiration. The respiration rate of a healthy adult is approximately 14–18 respirations per minute and the tidal volume of air associated with breathing is approximately 0.5 L [24]. Exhalation expels CO₂ in an amount that is approximately 5% of the total volume of gas released. The amount of CO₂ expelled by a healthy adult at rest is approximately 0.35–0.45 L/min. On average, an adult will release about 1.0 kg (580 L at 1 atm and 25° C) of CO₂ per day. CO₂ is generated during metabolism at a rate that is dependent on the physical activity of the individual. Higher levels of exhaled CO₂ are associated with the production of higher levels of bioaerosols as both are byproducts of breathing. Heightened levels of bioaerosols increase the risk of infection for both patients and staff in an OR. High levels of CO₂ in a room

are also associated with discomfort and reduced cognitive abilities [25–29]. Understanding how the level of CO₂ correlates with the number of occupants in an OR and incorporating CO₂ sensing devices into clinical settings will provide significant insight into assessing factors that lead to post-operative wound infections [30].

CO₂ detectors are readily available from a large number of manufacturers. While they have been used in a variety of environments, their utility in an OR would be clearer if carefully assessed in a controlled OR environment. Electrochemical gas sensors are subject to false readings from interfering gases. In comparison, NDIR (non-dispersive infrared) gas sensors [31, 32] are advantageous in that the readings are not affected by the presence of other gases as the characteristic IR absorption band of CO₂ at approximately 2350 cm⁻¹ (4.26 mm) does not overlap with common gases. Note that CO shows absorption maxima between 2100 and 2200 cm⁻¹, which provides sufficient spacing to distinguish CO₂ from CO. Additionally, NDIR sensors last longer and do not lose accuracy over time, whereas electrochemical sensors have a reduced shelf-life and wear out more quickly with usage as the electrolyte is consumed. Temperature and humidity can also reduce an electrochemical sensor's lifetime. Importantly, NDIR sensors can measure CO₂ concentrations below the ambient outdoor level of 400 ppm, whereas metal-oxide semiconductor-based sensors (a type of commercially available electrochemical sensor) generally have a lower limit of 2000 ppm, which is well above common ambient levels and therefore likely not suitable for measuring room occupation when few people are present [33]. While

photoacoustic IR sensors that utilize micro-electromechanical systems technology appear to be exceptionally reliable, they are expensive relative to NDIR sensors and can cost over \$40000 for one unit.

In this study, we examine the behavior of CO₂ levels relative to the number of people and activity level in a simulated OR environment. We show that as the number of people in the room increases, the CO₂ sensor detects a higher level of CO₂ in the air (measured in ppm). The sensor used is sensitive enough to detect a single active individual in an enclosed OR with air circulation conditions of 20 air changes per hour (ACH) and positive pressure, which meets the ventilation requirements for an OR according to the American Society of Heating, Refrigeration and Air-Conditioning Engineers specification ASHRAE 170–2017. The performance demonstrated will facilitate selection of available technologies for use in future experiments and more complex systems for monitoring occupation level. The results provide fundamental data regarding CO₂ accumulation in an OR that healthcare professionals can use to assess CO₂ detection as a means to better understand and manage the occupation level and accumulative respiration in surgical environments. Awareness of occupation levels on air quality will encourage new and effective approaches to risk management strategies for minimizing surgical site infections. Note that while we focus on occupation level, it is also important to track the accumulation of respiratory byproducts which can contain harmful bioaerosols. While infectious agents might be difficult to detect, monitoring the changes in CO₂ concentration provides a detectable proxy that can indicate if the byproducts of breathing are able to accumulate despite the presence of heavy air flow and positive pressure. We show that the CO₂ level can accumulate as an individual breathes in an enclosed well-ventilated OR and that the CO₂ concentration is dependent on the number of people in the room, which indicates that the relative contamination level of the air in an OR increases as people enter the room, even at standard OR ACH levels and positive pressure.

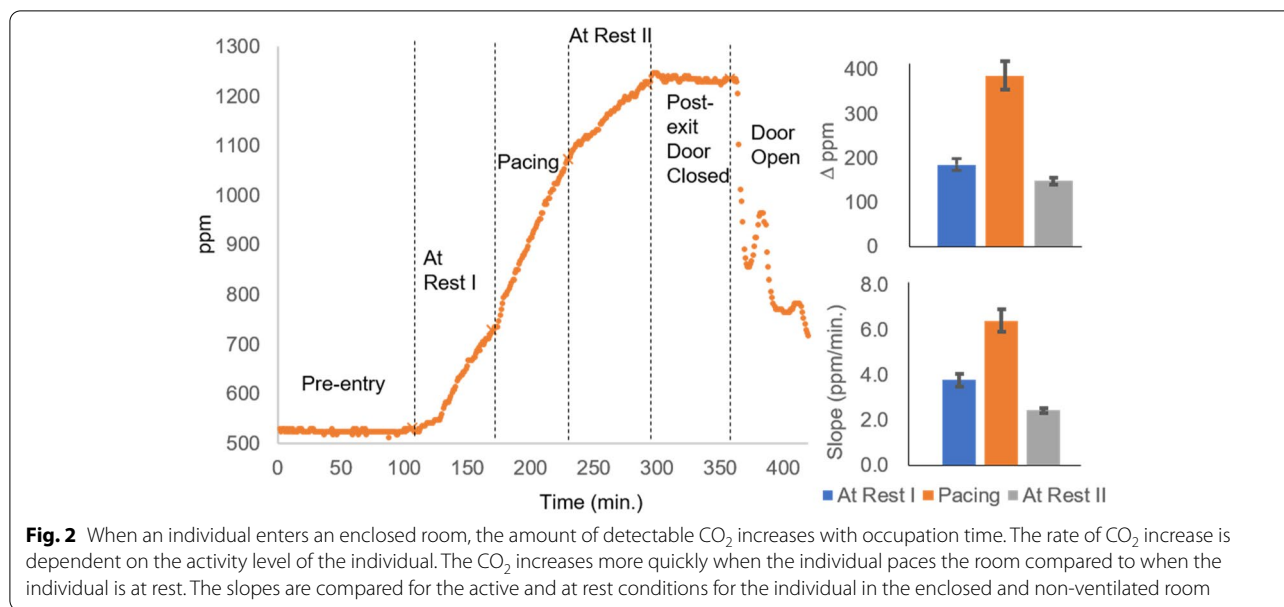
Methods

Testing was performed in a 50 m³ operating room simulator, which included central ceiling-mounted ducts directing HEPA-filtered supply air and four lower wall mounted air return ducts. The system supplied 20 air exchanges per hour (ACH) and 0.03 in. H₂O (7.5 Pa) of positive pressure to the outside environment. The room was equipped with typical OR air flow obstructions including surgical lights, tables and medical equipment (Fig. 1). Two calibrated Aeroqual 500 NDIR CO₂ sensors (Gas Sensing) were used to measure the concentration of CO₂. This sensing device can measure CO₂

concentrations in the range of 0–5000 ppm with a resolution of 1 ppm. All measurements were performed at ambient temperature. Data was collected electronically and downloaded to an external computer for analysis using Aeroqual Series S500 Monitor Software V6.5 and Microsoft Excel. The sensors were placed in the perimeter of the OR because the perimeter is more contaminated than the center. The first sensor was placed approximately 58 cm from a wall containing the entry/exit door. The sensor was approximately 2.4 m from the door and approximately 1.8 m from the head of an operating bed in the middle of the room. The second sensor was placed approximately 58 cm from the opposite wall and approximately 2.4 m from the head of the operating bed and approximately 5.3 m from the door. The two sensors were approximately 4.6 m apart. Sensor readings were taken at 60 s intervals. For occupancy data, adults walked in the room for 20 minutes at a moderate pace in a circular path, changing direction every 5 minutes. The door was kept closed during the experiments. For occupancy data, the change in CO₂ immediately before entering the room was compared to the CO₂ concentration upon exit. For three-hour single occupancy experiments, an adult rested in a chair for the first hour of occupancy, walked in the room for 1 hour at a moderate pace in a circular path, changing direction every 5 minutes, and rested in the chair for the final hour.

Results and discussion

In order to understand the sensitivity of our sensor to human respiration in an enclosed room, we initially monitored the change in CO₂ concentration when one adult human resides in a simulated OR at ambient pressure and without ventilation. Two sensors were placed near opposite walls in the room in order to understand whether or not large spatiotemporal fluctuations in CO₂ concentration develop. The CO₂ level as a function of time for a representative trial is shown in Fig. 2 (sensor 2 data shown; see supporting information S1 for sensor 1 and subsequent trials data). Prior to entry, the background level of CO₂ in the room was relatively constant, fluctuating around 525 ppm. After the individual entered the room and assumed a resting position seated in a chair, the CO₂ level increased by approximately 200 ppm over a period of 1 hour. After 1 hour at rest, the individual stood up and walked in a circular path around the OR for 1 hour, reversing direction every 5 minutes. The increased activity level produced a faster rate of CO₂ accumulation in the enclosed room, increasing by 350 ppm after 1 hour. After 1 hour of pacing the OR, the individual re-assumed the initial resting position. The CO₂ level continued to rise, but at a reduced rate compared to the first and second hours in the OR, increasing by 156 ppm after 1 hour

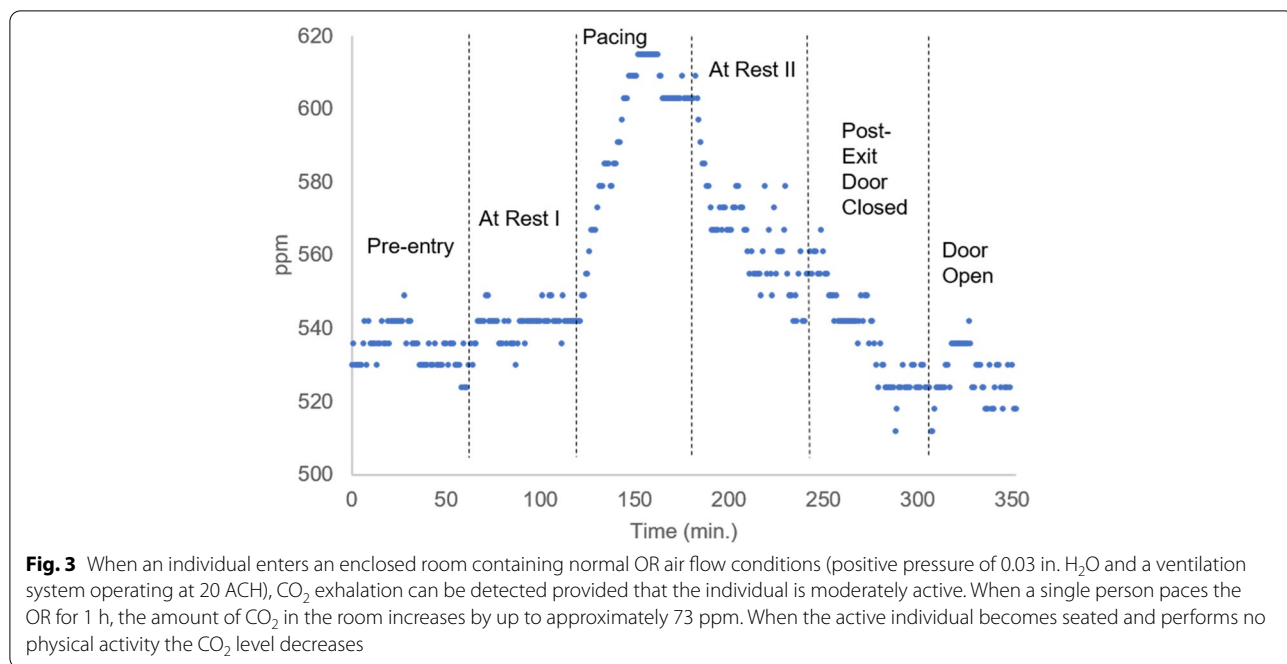


and bringing the total concentration to approximately 1259 ppm, which is approximately 2.4 times the initial background level. The individual then left the room, closing the door after exiting. The CO₂ level remained relatively constant while uninhabited. After monitoring the CO₂ level in the empty room for 1 hour, the door was propped open. The CO₂ level rapidly reduced as the door remained open. Replication of the experiment multiple times showed consistency in the total change and rate of change in CO₂ concentration for both sensors (See S1, S2, S3, S4 and S5).

The average change in CO₂ concentration and average slope for each of the three hours spent in the room are shown in the bar graph on the right in Fig. 2. The rate of CO₂ accumulation consistently increases when the individual transitions from a resting state to moderate activity, and consistently decreases when the individual re-assumes a resting state. The average slopes for the initial resting phase (At Rest I), the active phase (Pacing) and the second resting phase (At Rest II) are 3.8 ± 0.3 ppm/min., 6.4 ± 0.5 ppm/min. and 2.4 ± 0.1 ppm/min, respectively. The average change in CO₂ for the corresponding phases are 190 ± 10 ppm, 390 ± 30 ppm and 150 ± 7 ppm, respectively. The results show that a single individual can considerably increase the concentration of CO₂ in a room and, by extension, affect the quality of the air. Importantly, an individual's contribution to the CO₂ level in a room can be reliably detected with a portable NDIR sensor and the rate of increase corresponds to the occupant's activity level. Higher activity increases metabolic rate which in turn increases CO₂ production. A recent study has similarly concluded that measured

CO₂ generation rates are positively associated with physical activity levels [18]. In all trials the CO₂ level did not exceed 1400 ppm, which is below the Occupational Safety and Health Administration (OSHA) permissible exposure limit of 5000 ppm (averaged over 8 hours), however, the need for awareness is apparent. As noted above, a growing body of cross-disciplinary literature in fields that include cognitive psychology, indoor air quality and neuroscience suggests that increasing CO₂ concentrations can impair cognitive function. For example, Allen et al. [25] reported declines in "cognitive function scores" when indoor CO₂ levels were increased from approximately 500 ppm to approximately 950 ppm, and greater declines when the CO₂ level was raised to approximately 1400 ppm. Activities that involve increasing amounts of time and/or number of people in an enclosed space with limited ventilation could produce CO₂ levels above permissible limits or exceed levels associated with compromised cognitive performance.

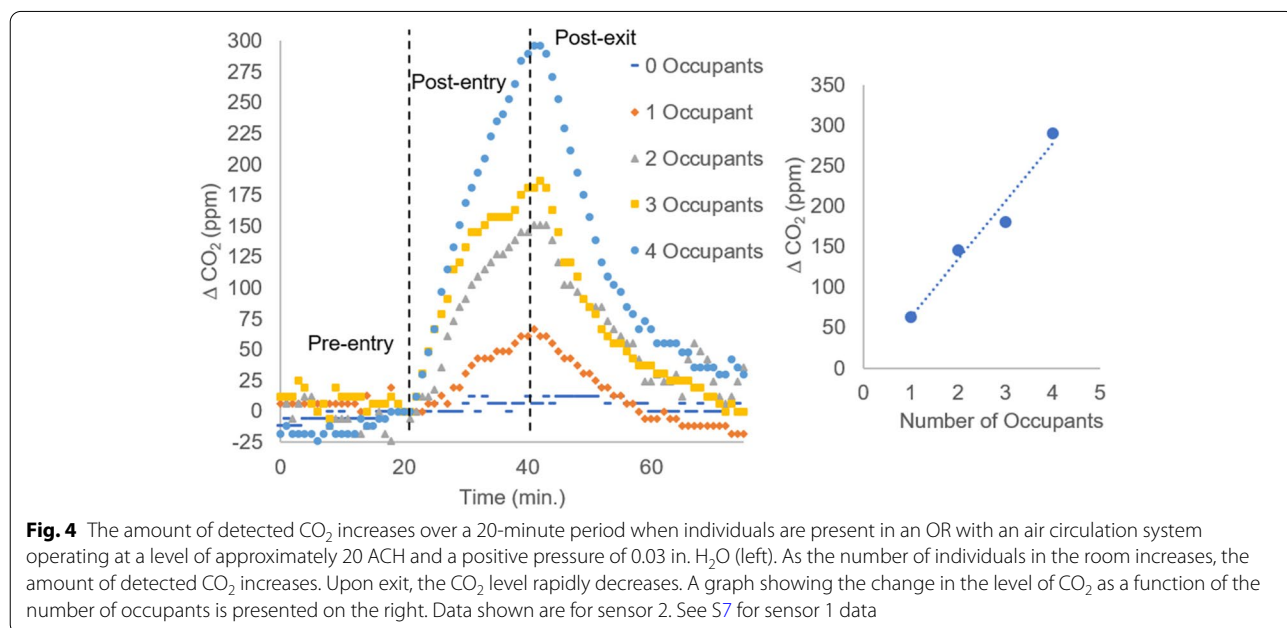
In order to understand if metabolic CO₂ production can be detected in an OR operating at standard conditions, we repeated the experiment under standard OR airflow conditions. The room ventilation operated at 20 air changes per hour (ACH) with a positive room pressure of 0.03 in. H₂O. Figure 3 shows the CO₂ concentration as a function of time for an individual in the enclosed OR. When at rest, it is very difficult to detect occupancy due to the air flow conditions. When the individual begins to walk in the room as described above, the CO₂ level increases with time. After one hour of walking the maximum change detected was approximately 73 ppm. Similar results were obtained with the additional sensor



in the room (see S6). This result shows that while the air circulation system and positive pressure have a beneficial effect on the air quality, it does not completely eliminate the respiratory influence on the air composition. The metabolic CO₂ production of a single person can be detected even with standard OR air flow conditions, indicating that the exhalation products of one person can

accumulate at a rate that is higher than its displacement by the ventilation system.

In order to understand if the CO₂ level increases with the number of individuals in an OR, we monitored the CO₂ level when occupied by a pre-selected number of individuals for a period of 20 minutes under normal OR air flow conditions. Figure 4 shows a graph of change in CO₂ level as a function of time for different quantities of



occupants. The presence of a single individual pacing the room produces a clear rise in CO₂ concentration. After repeating the experiment three times the average increase for sensors 1 and 2 show accumulations of approximately 54 ± 7 ppm and 59 ± 9 ppm, respectively. After exiting and ensuring that the door was closed, the detected CO₂ concentration briefly increases before showing a long-term attenuation to the baseline level as shown by the representative trace in Fig. 4. As the number of occupants in the room increases, the CO₂ level increases. When four occupants pace the room for 20 minutes, the CO₂ level increases by 290 ppm. When three and two occupants pace the room for 20 minutes, the respective CO₂ concentrations are 181 and 145 ppm. A graph on the right in Fig. 4 displays the change in CO₂ concentration as a function of the number of occupants that were in the room. Under the conditions employed, the CO₂ rises in a linear fashion. These results show that as the number of people in a room increases, the CO₂ concentration increases, even under air purifying ventilation standards that are encountered in an OR. Note that the levels of CO₂ obtained will vary with individuals, activity levels and ventilation rates, however, our data shows a clear trend indicating that higher CO₂ levels are detected when the number of occupants in a room increases. A difference of one person is enough to detect a change in CO₂ concentration.

In order to minimize surgical site infections, it is important to maintain clean air in an OR. Individuals introduce a number of viable and non-viable impurities to the air in an OR through various mechanisms including shedding, displacing particulate matter at rest on a surface and breathing, the latter of which produces CO₂ [34–37]. We have demonstrated that changes in CO₂ concentration provide a biomarker of human presence that can be detected even under air flow conditions of 20 ACH and positive pressure. Tracking CO₂ level in an OR can help manage human traffic and facilitate the epidemiology of surgical site infections. Although well-managed ORs are ventilated and in many cases under positive pressure, our results show that the presence of one breathing individual creates detectable changes in the composition of the air in a properly ventilated OR. While at relatively low concentrations CO₂ itself is benign, it provides a proxy for more harmful substances that are emitted via expiration, including the highly disruptive SARS-CoV-2 which causes COVID-19 [23]. Additionally, a number of health effects associated with rising CO₂ levels in an enclosed space include drowsiness, loss of concentration, nausea, headaches and more severe consequences associated with oxygen deprivation as higher concentrations are reached [38]. Gaining an awareness and understanding of the effect of occupancy time and population on the CO₂ concentration in an OR will facilitate public health risk

management and spur the development of new technologies for using CO₂ to track the occupancy and respiratory history of an OR during surgery. In combination with good ventilation, particle filtration, PPE and UV disinfection, CO₂ monitoring can be employed in the toolbox of techniques used to manage, assess and prevent hospital acquired infections.

Conclusion

We have shown that the concentration of CO₂ in an enclosed operating room increases as the room is populated. While the magnitude of increase is lower when the room is well-ventilated with positive pressure, the accumulation of CO₂ over time reaches detectable levels and was shown to increase as more individuals occupied the room for a given amount of time. This study has important implications for developing systems for monitoring CO₂ accumulation as well as building awareness for the involuntary and unavoidable contamination of the air in ORs upon human entry. Monitoring CO₂ levels in an OR will provide critical information that can help mitigate risks that can lead to transmission of infections.

Abbreviations

CO₂: Carbon dioxide; OR: Operating room; SSI: Surgical siteinfection.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s13037-022-00343-8>.

Additional file 1: S1. Sensor 1, trial 1 (see Figure 1 for sensor 2 data): CO₂ concentration as a function of occupation time for a single individual in an enclosed OR with no ventilation. **S2.** Sensor 2, trial 2: CO₂ concentration as a function of occupation time for a single individual in an enclosed OR with no ventilation. **S3.** Sensor 1, Trial 2: CO₂ concentration as a function of occupation time for a single individual in an enclosed OR with no ventilation. **S4.** Sensor 2, Trial 3: CO₂ concentration as a function of occupation time for a single individual in an enclosed OR with no ventilation. **S5.** Sensor 1, Trial 3: CO₂ concentration as a function of occupation time for a single individual in an enclosed OR with no ventilation. **S6.** Sensor 1: When an individual enters an enclosed room containing normal OR airflow conditions (positive pressure of 0.03 in. H₂O and a ventilation system operating at 20 ACH), CO₂ exhalation can be detected provided that the individual is moderately active. **S7.** Sensor 1 data: The amount of detected CO₂ increases over a 20-minute period when individuals are present in an OR with an air circulation system operating at a level of approximately 20 ACH and a positive pressure of 0.03 in. H₂O.

Acknowledgements

Not applicable.

Associated context

Supporting information: Additional CO₂ detection data for Sensor 1 and for multiple trials are included in the supporting information free of charge (PDF).

Authors' contributions

The manuscript was written through the contributions of all authors. All authors have given approval to the final version of the manuscript.

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Availability of data and materials

All data generated and analyzed in this study are included in this publication and the supporting information file.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

GC and DK are employed by Aerobiotix, Inc., which develops, manufactures and sells air cleaning equipment, however, the equipment used in this study is not developed, manufactured or sold by Aerobiotix, Inc.

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