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A Peripherally Located Air Recirculation Device Containing an Activated Carbon Filter Reduces VOC Levels in a Simulated Operating Room

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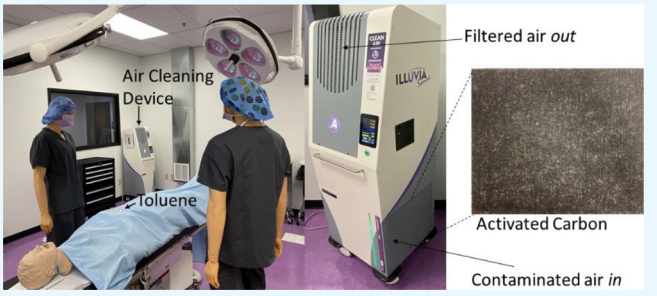
ABSTRACT: Electrosurgery procedures produce airborne contaminants including volatile organic compounds (VOCs). The effectiveness of commercial grade activated carbon at removing toluene, a typical VOC, from the air in an enclosed simulated operating room (OR) when interfaced with an air recirculation device was tested. The concentration of toluene in the air was measured using gas sensitive semiconductor VOC sensors. When the air recirculation device containing activated carbon was turned *on*, the concentration of toluene in the air decayed exponentially. When the device was *off*, the toluene concentration reduced much more slowly. After 130 min, a VOC sensor placed near the air recirculation device showed VOC reductions of approximately 30% when the device is *on* and less than 1% when the device is *off*. Changing the activated carbon filter after 22 h of constant use showed an abrupt increase in the rate of toluene removal.



INTRODUCTION

Volatile organic compounds (VOCs) are pervasive air pollutants and are associated with negative health effects.[1,2] The World Health Organization (WHO) indicates that VOCs have boiling points of less than 250 °C at standard pressure (1 atm, 101.3 kPa), with further subdivisions.[3,4] In general, any organic molecule that evaporates or sublimates into the air at applicable temperature and pressure can be considered a VOC. Some common VOCs, including benzene and formaldehyde, are classified as carcinogenic to humans.[5−7] VOCs are prevalent in buildings, homes, and cars and pollute indoor spaces via off-gassing from various materials,[8,9] outdoor air pollution entering residential and occupational spaces (car emissions, engineering activities, geological activity, etc.),[10−12] and various indoor activities (cooking, use of cleaning agents, etc.).[13] VOC reduction in operating rooms (ORs) is of particular importance because ORs are regularly contaminated with VOCs during essential surgical procedures.[14] For example, electrosurgical procedures produce smoke plumes that contain a broad range of VOCs with more than 80 being identified.[15−19] Efforts aimed at removing surgical smoke hazards in ORs must include mitigating the buildup of VOCs to protect both staff and patients from breathing high quantities of toxic chemicals. Note that ASHRAE 170 indicates minimum ventilation requirements for healthcare facilities (currently 20 ACH and positive pressure).[20] This specification is not necessarily adequate in all situations and does not measure a specific outcome in regards to contamination levels. VOCs in hospitals are not limited to the OR. Thomas et al. measured more than 40 VOCs in various locations of a teaching hospital including the reception area.[21] The risk of exposure to VOCs in the OR merits investigating and demonstrating practical processes for their reduction in nosocomial environments.

Developing and testing VOC mitigating materials is an ongoing challenge.[22−25] While a variety of porous materials that adsorb small molecules have been realized,[26] in practice activated carbon[27−29] is widely used for VOC removal due to its low cost, durability, ease of use, low hydrodynamic resistance, widespread commercial availability, and general flexibility in interfacing with various equipment types. Additionally, activated carbon requires no external energy source such as heating or irradiation to function via physisorption, nor does it require cooling to low temperature. The expansive surface area of activated carbon creates a multitude of sites for binding small molecules and removing VOCs from the air primarily via surface adsorption, minimizing the likelihood of undesired byproducts that are associated with some materials that remove VOCs primarily via catalytic

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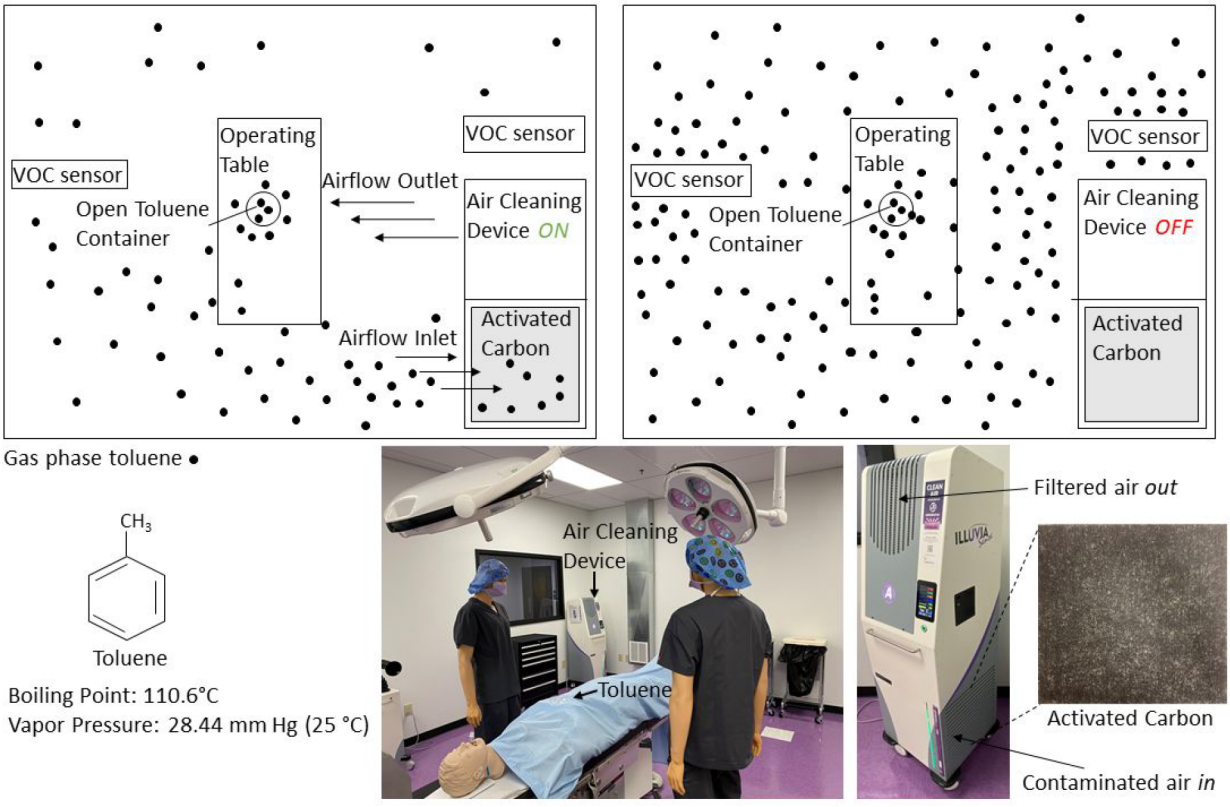

Figure 1. Experimental setup consists of a simulated OR containing an air cleaning device equipped with an activated carbon filter. The room is polluted with toluene prior to activating the device. When the air cleaning device is *on*, toluene-polluted air encounters the activated carbon filter as it is transported through the machine, reducing the overall concentration of toluene in the room over time as it binds to the activated carbon surface.

reactions.[30] It should be noted, however, that activated carbon is a structurally rich material, and its interactions with gases and liquids under various environmental parameters are not limited to physisorption.[31] In general, the structural features of activated carbon are complex and vary based on preparation conditions. These features include pore size and chemical composition. The exact properties will depend on the processing conditions and carbon source.[32−36] Non-VOC gas-phase molecules such as water vapor can affect the efficiency of the process.[37] The complex and variable structure of activated carbon suggests that its effectiveness should be tested when introducing to air cleaning devices for specific applications.

Many studies have investigated the adsorption of VOCs to activated carbon-based materials. Typically, adsorption is studied by generating isotherms that show the amount of material adsorbed at equilibrium at constant temperature as a function of pressure.[38] While many reports have established fundamental relationships between the interaction of activated carbon with various substances, they are typically performed at very low air flow values of the incoming gas[39] and are not reminiscent of face velocities encountered in field settings. It is necessary to assess the efficiency of VOC removal in application-oriented studies, particularly in OR settings where the air is subject to heavy contamination and hence compromises the environment of care. FDA approved portable air filtration systems are currently in use in nosocomial settings and have been shown to effectively remove various contaminants.[40−43] It is of interest to show that the decontamination abilities of these types of devices are extended to VOC removal in OR spaces. Experiments that interface activated carbon with air cleaning devices operating at relatively high air flow in healthcare settings will elucidate the potential benefits of adoption.

In this study, we demonstrate an appreciable reduction in VOC levels in a simulated OR using a medical grade air recirculating device equipped with an activated carbon filter. The device was stationed in the periphery of the room near a corner, allowing it to be integrated into the OR without obstructing movement of individuals or consuming space near the operating table. We used toluene as a representative VOC. Importantly, toluene is a well-known byproduct of electrosurgery for a variety of tissue types.[15] Additionally, toluene is a well-recognized VOC that is an air contaminant in many processes.[39,44] The propensity of the device to remove toluene from the air demonstrates that carbon-based filtration is an effective tool for enhancing the environment of care.

MATERIALS AND METHODS

Experiments were performed in a 50 m^3 simulated OR[45] as shown in Figure 1. The room was equipped with typical OR air flow obstructions including surgical lights, tables, and medical equipment. The room also contained three healthcare worker manikins, one of which was lying on an OR bed. The other two stood upright on opposite sides of the bed. An Illuvia Sense (Aerobiotix, Miamisburg, OH) air-cleaning device that recirculates local air back into the room at a rate of 450 cfm after passing through HEPA filtration and a UV chamber was present in the corner of the room and used as the air recirculating device in this study. An activated carbon filter

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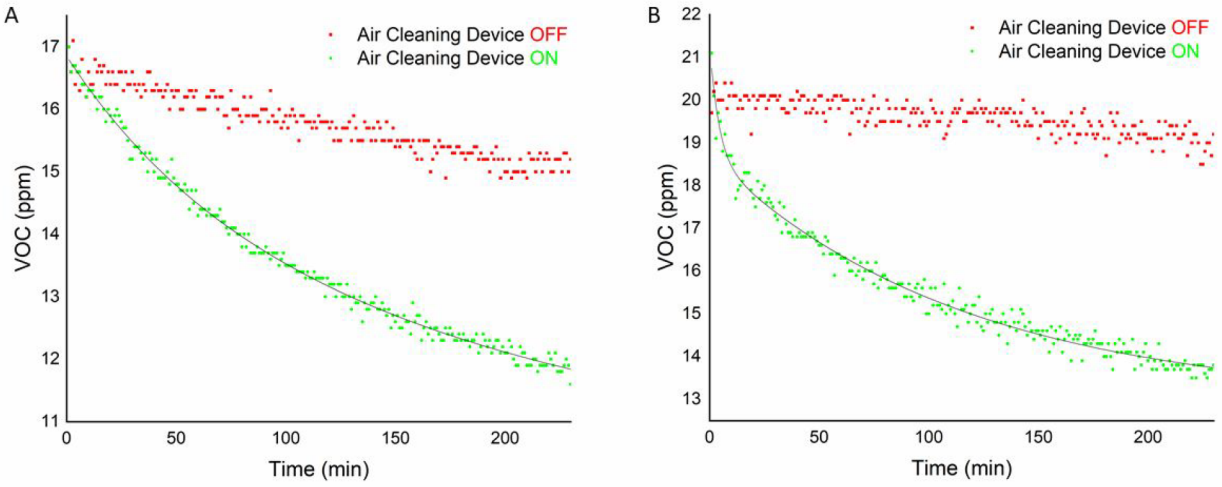

Figure 2. Concentration of toluene in the OR as a function of time is shown when the air recirculation device is *on* (green) and *off* (red). Data for sensor 1, 18 ft from the air cleaning device (A), and sensor 2, 7 ft from the air cleaning device (B), are shown.

(ultrafiber cm108) (Troy Filters) measuring approximately 46 × 46 cm^2 was placed in a slot at the air inlet of the air recirculating device. The activated carbon filter had a thickness of approximately 0.3175 cm and a density of approximately 0.034 g/cm^3. The activated carbon filter was positioned just behind the inlet of the device so that when the device is *on* all incoming air is forced to pass through it. Toluene was purchased from Aldrich and used as the VOC in the experiments. VOCs were measured with calibrated Aeroqual (Aukland, New Zealand) gas sensitive semiconductor VOC sensors (Series 500) that measure from 0 to 25 ppm with an accuracy of ±0.1 ppm ± 10% and a resolution of 0.1 ppm. Two VOC sensors were placed in the room at designated locations depicted in Figure 1. Sensor 1 was stationed near the opposite corner of the room, approximately 18 ft from the outlet of the air recirculating device. Sensor 2 was stationed near the same wall as the air cleaning device and approximately 7 ft from the air outlet. Readings were taken every minute. A glass-capped dish of toluene was brought into the room. After placing the dish on top of the sternum of a manikin resting on an operating bed in the middle of the room, the cap was removed, allowing toluene to evaporate into the OR air. When detected VOCs reached a level of approximately 17 ppm on sensor 1, the toluene was covered and removed from the room. Note that the simulated OR contains three glass windows, allowing for the sensors to be viewed without entering the OR. The VOC levels were monitored with the air recirculating device *off* and *on*. After monitoring VOC levels for 22 h with the air recirculating device *on*, the carbon filter was removed and immediately replaced with a fresh carbon filter. This exchange process took less than 5 s. The used carbon filter was immediately removed from the OR. The room ventilation system was not in operation during the experiments to reduce the rate of natural gas exchange, and the door remained closed except for when entry was necessary. Data were collected electronically and downloaded to an external computer for analysis and processing using Aeroqual Series S500 Monitor Software V6.5, Microsoft Excel and OriginPro 2022. Biexponential fitting of the toluene decay when the device is *on* had an R^2 value of 0.99377.

RESULTS AND DISCUSSION

The propensity for an activated carbon filter to remove organic pollutants from the air of an OR when interfaced with a medical grade air cleaning device was assessed by monitoring the VOC levels in the room with the air recirculating functionality of the device *on* and *off*. The room was prepolluted with toluene, a surgically relevant and common VOC. Figure 2 shows the VOC levels in ppm as a function of time for sensor 1 (18 ft from the device, near wall on opposite side of room) and sensor 2 (7 ft from the device, near wall on same side of the room) over a period of 230 min, which approximately matches the upper range of operating times for various surgeries reported in a recent study (mean of 130 ± 97 min).[46] Data from both sensors show that the concentration of toluene in the air reduces at a much greater rate when the machine is *on* compared to when it is *off*. While the door was kept closed and the room contains no open windows, natural loss of toluene is not unexpected as Brownian motion of the toluene gas will predictably find escape routes in the inherent room crevices (ventilation openings, ceilings panels, etc.); however, when air is channeled through the activated carbon filter, the VOC levels diminish rapidly. After 130 min, sensor 1 readings show that detected VOC levels are reduced by approximately 25% when the air cleaning device is *on*. In contrast, the VOC levels are reduced by only 6% when the device is *off*. Sensor 2 shows similar reductions of 30% when the device is *on* and less than 1% change when the device is *off*, indicating that, spatially, the air content change is similar near and far from the position of air recirculation through the activated carbon filter. VOC decays obtained when the device was *on* were fit with a biexponential decay. For sensor 1, two time constants (T_1 and T_2) of 69 ± 2 and 790 ± 40 min were extracted from the fitting and differ by an order of magnitude. Similarly, for sensor 2, time constants (T_1 and T_2) of 42 ± 2 and 640 ± 3 min were extracted. The biexponential decay implies at least two processes are occurring and could be related to natural loss of VOC in combination with adsorptive capture by the activated carbon or different adsorption processes with differing rates occurring at the surface of the activated carbon. It is worth noting that dynamics at surfaces have previously been shown to require biexponential fitting to properly model their kinetics.[47] The similarity in the decay

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profiles for both sensors shows that the use of the activated carbon filter effectively reduces VOCs throughout the OR regardless of vicinity to the air recirculation device.

To further demonstrate that the activated carbon filter reduces the concentration of toluene in the air, we inserted an activated carbon filter into the device immediately after monitoring VOC levels with the device *off*. After insertion, the device was immediately turned *on*. All other room conditions were kept the same. Figure 3 shows how the

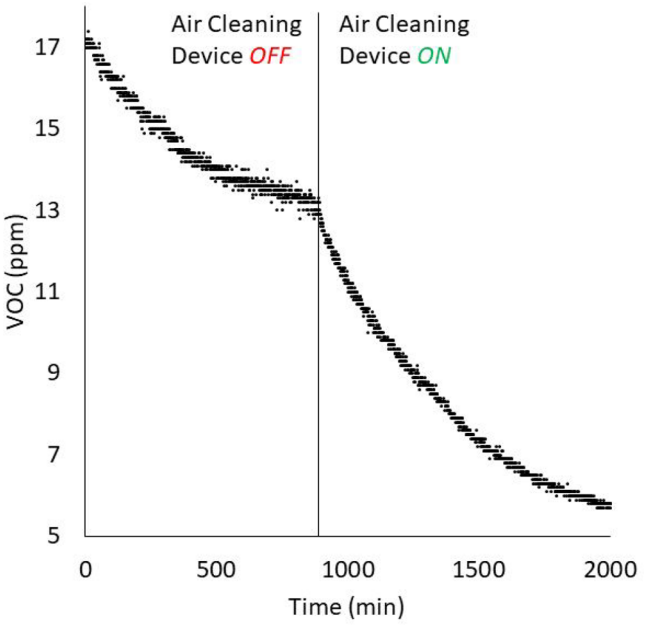

Figure 3. VOC concentration is shown as a function of time when the air filtering device is *off* and when the device is switched *on* immediately after monitoring for 15 h while it was *off*. VOC data were collected for approximately 15 h while the air filtering device was *off*. The solid line indicates the point at which the device was turned *on*.

VOC levels undergo an abrupt and rapid reduction when the device equipped with an activated carbon filter is turned *on* immediately after monitoring for several hours with the device *off*. The abrupt and discontinuous change in VOC reduction occurs once the air is forced to flow through the activated carbon filter, showing that differences between the *on* state and *off* state cannot simply be explained by natural physical changes such as thermal gradients, humidity levels, or changes in barometric pressure.

Filters based on surface adsorption lose binding sites over time and become saturated as they adsorb pollutants. Replenishing uncontaminated surface area by inserting a fresh filter is expected to increase the rate of VOC reduction. After 22 h of running the device in the contaminated OR, the used activated carbon filter was removed. Upon insertion of a fresh sheet of activated carbon the rate of VOC reduction showed a clear increase as presented in Figure 4. This further supports the effectiveness of interfacing activated carbon with the air recirculating device.

The use of activated carbon to remove VOCs from the air is a known technology; however, it is often overlooked that the binding strength of VOCs to activated carbon will change with molecular structure and whether or not the surface of the activated carbon was chemically modified. As a result, much of the literature regarding this topic requires careful assessment.

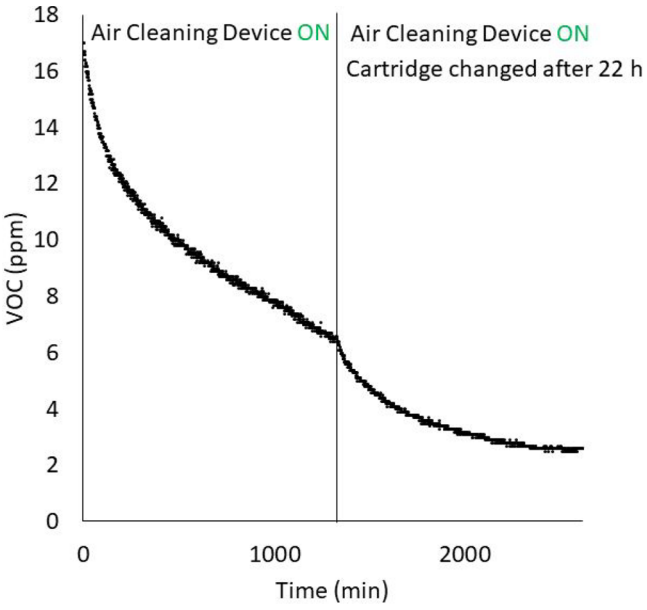

Figure 4. Concentration of toluene in the OR air is shown as a function of time with the air recirculation device *on* and immediately after removing a used carbon filter and adding a fresh carbon filter. The solid line indicates the point at which the activated carbon filter was changed.

In addition, the effectiveness of a thin sheet of activated carbon in a specific application requires testing as the size of the room, airflow, and physical barriers can affect transport to the surface of the activated carbon film. In addition, the strength of surface binding can potentially be affected by the airflow conditions of the device. In an OR environment, devices must conform to applicable regulations; therefore, it is important to test the efficacy of the approved equipment. The device used in this study is FDA approved for biomedical applications and is currently used in ORs to maintain clean air. In an OR, toluene and other VOCs are produced as a byproduct of electrosurgery. The commercially available activated carbon used in this study is effective at removing toluene from the OR air as shown by the data in Figures 2−4. Note that a sensor 18 ft from the air cleaning device shows clear reductions in detected VOC levels, demonstrating that VOCs are reduced throughout the room and not just in the local vicinity of the air recirculating device. It is important to highlight that the gas phase toluene was not directed to the device via tubing. Instead, the toluene was allowed to pollute the air as it would in a surgical procedure. The device's own airflow directing capabilities were the only influence on delivering the toluene to the surface of the filter. Given the known propensity of aromatic molecules to interact with pi-saturated surfaces, we expect similar reductions in structurally related VOCs. Note, however, that one cannot simply extrapolate toluene reduction to all VOCs. For example, polar molecules are expected to adsorb less effectively. Additionally, different sources of activated carbon might have different surface functionality and cleanliness. Given the variable structural aspects of activated carbon and devices used to realize its VOC mitigating capabilities, field studies that challenge air cleaning devices under applicable environmental conditions will shed further light on best practices for managing occupational environments exposed to hazardous chemicals.

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We have shown that a medical grade air recirculating device running at 450 cfm and equipped with an activated carbon filter significantly reduces gas phase toluene, a common and surgically relevant VOC, from the air in an enclosed simulated OR. VOC levels are reduced by approximately 25−30% within the first 130 min. Changing the activated carbon filter after more than 20 h of air recirculation abruptly increases the rate of VOC removal, underscoring the importance of properly maintaining air cleaning devices with fresh material on a regular basis. Running the device during electrosurgical procedures is expected to reduce contamination in the OR air and particularly in the perimeter of the room which is the most polluted area of a surgical environment. Combining supplementary activated carbon filtration with standard air changes and positive pressure will help improve environmental conditions in ORs.

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Notes

The authors declare the following competing financial interest(s): G.C. and D.K. are employed by Aerobiotix, which manufactures the air cleaning device used in this study.

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