Aerosol and Air Quality Research, x: 1–10, xxxx

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2016.05.0191

Influence of Surgical Smoke on Indoor Air Quality in Hospital Operating Rooms

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ABSTRACT

The objective of this study is to analyze the volatile organic compounds (VOCs) in the surgical smoke generated during laparoscopic surgery, and determine their influence on the indoor air quality in hospital operating rooms (ORs). Field measurements were carried out during eight surgeries in conventional and robotic ORs in which an electrosurgery system was being used, thus continuously generating surgical smoke. The VOCs were measured at three different locations, in the patients' abdominal cavities, beside the surgical table, and at the exhaust vent. Other indoor pollutants including carbon monoxide (CO), carbon dioxide (CO_2), and total airborne bacteria (TAB) in the indoor air were measured at the exhaust to assess the general indoor air quality in the ORs. The results from the patients' abdominal cavities confirmed that the surgical smoke contained abundant VOCs, with the levels of benzene and toluene exceeding the health guidelines. Compared to the results obtained in the abdominal cavity, the measurements obtained at the surgical table and exhaust vent exhibited low levels of VOCs, indicating that the actual exposure to these compounds was minimized in a highly-ventilated operating room. However, the benzene concentration in the operating room approached a level that threatens the health of the occupants. Therefore, the results of this study suggest that there is a potential health risk to the surgeon who is closest to the point of origin of the surgical gas, as well as a need for further attention to identify the local pollutant dispersion near the surgical table while the ventilation system is operating.

Keywords: Surgical smoke; Hospital operating room; IAQ; Volatile organic compounds (VOCs)

INTRODUCTION

The maintenance of a high indoor air quality (IAQ) in a hospital is important to ensuring successful patient care and health outcomes (Choosong and Phakthongsuk, 2006; Chuaybamroong *et al.*, 2008; Huang *et al.*, 2013). In operating rooms (ORs), the challenge is to achieve infection control and safety for the benefit of the patients and surgical staff. The air quality is essential to infection control and reducing the number of surgical site infections (SSIs). SSIs are regarded as being one of the most common causes of serious surgical complications (World Alliance for Patient Safety, 2008) and account for 14% to 17% of all hospital-acquired infections (Centers for Disease Control and Prevention, 2004; Weigelt *et al.*, 2010). Air quality control is also significant for achieving safety and comfort, which are directly associated with the well-being and productivity of personnel. Surgical gas generated by the use of anesthetic gas, lasers, and other surgical energy-based devices is regarded as constituting a threat to the surgical staff (Ball, 2001; Ulmer, 2008). To provide a high level of IAQ in ORs, many studies on OR ventilation system have been conducted (Chow and Yang, 2003; Balaras *et al.*, 2007; Liu *et al.*, 2009; Chow and Yang, 2012), and standards and guidelines for the air quality in ORs have been proposed, focusing on general OR ventilation requirements, e.g., the minimum total air exchange rate and outdoor air exchange rate, as well as air flow design to reduce pollutant entrainment (NFPA, 2005; AIA, 2006; ASHRAE, 2008; FGI, 2010).

Concerns about surgical smoke have been raised with the application of laser and electrosurgery technologies. Surgical smoke is usually generated by the interaction of tissue and the heat-producing equipment used for dissection and hemostasis. Although considered part of the patient care environment, the burning process nevertheless leads to the generation of combustion gases, producing carbon monoxide (CO), particulates, and other harmful pollutants (King and McCullough, 2006; Watson, 2010) according to surgical types and instrument used (Mowbray *et al.*, 2013). Several organizations have warned that patients and surgical staff

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are at an increased risk of developing health conditions associated with exposure to surgical smoke (King and McCullough, 2006). Many previous studies have focused on particle characterization in surgical smoke and its infection risks. Mowbray *et al.* (2013) systematically reviewed 20 full-text articles addressing surgical smoke and found that common end points were particle size (DesCoteaux *et al.*, 1996; Bruske-Hohfeld *et al.*, 2008; Andreasson *et al.*, 2009) and infection risk (Kunachak *et al.*, 1996; Capizzi *et al.*, 1998; Hughes and Hughes, 1998). It is in relatively recent years that the chemical composition in surgical smoke such as volatile organic compounds (VOCs) has been investigated. Al Sahaf *et al.* (2007) quantified the presence of toluene, ethylbenzene, and xylene in surgical smoke, which appeared in quantities similar to those in cigarette smoke. Hills *et al.* (2012) also reported that chemicals including benzene, toluene, styrene, formaldehyde could be found in surgical smoke. Mellor *et al.* (2013) concluded that there is a mixture of both hazardous chemicals and potentially infectious biological substances within surgical smoke. They also pointed out that, while the presence of hazardous substances had been identified, few studies had investigated the indoor air quality to which the medical staff are exposed.

A relatively new surgical technique, laparoscopic surgery, has become widely adopted for various surgical procedures. However, laparoscopic surgery, which is minimally invasive procedure, allows smoke to build up inside a patient's abdominal cavity, which may result in a high exposure risk to the OR personnel. Weston *et al.* (2009) noted that the surgical gases produced during laparoscopic surgery would be harmful to surgeons. Choi *et al.* (2014) performed a series of measurements on the surgical smoke generated by the electrocautery system during laparoscopic surgery, collected directly from the abdominal cavities of 20 patients. They analyzed the concentrations of 52 individual VOCs, including carcinogenic and non-carcinogenic compounds. These studies clearly identified the VOCs present in the surgical smoke collected from the abdominal cavities. However, their impact on the indoor air quality in an OR is still not clear.

As a part of a strategy to improve the indoor air quality in laparoscopic surgery ORs, a further study to quantify the indoor pollutants in surgical smoke and the indoor air in ORs was required. Such a study would contribute to an understanding of the exposure of patients and surgical staff to surgical smoke in different locations, and would act as a starting point for finding a suitable means of diluting or removing the smoke. The objective of the present study was to analyze the VOCs in the surgical smoke generated during laparoscopic surgery and their influence on the indoor air quality in hospital ORs. Field measurements were carried out during eight surgeries in two hospital ORs, in which an electrocautery system continuously generated surgical smoke. The VOCs were measured in surgical smoke taken directly from the patients' abdominal cavities. Gaseous pollutants including VOCs, CO, CO_2 and TAB in the indoor air of the ORs were simultaneously measured beside the surgical table and at the exhaust in order to analyze the general indoor air quality in ORs.

METHODS

Overview

Field measurements were carried out during eight laparoscopic surgeries in two hospital ORs where the use of electrocautery system continuously generated surgical smoke as shown in Table 1. One of the ORs was equipped with a robotic system, which required a room with larger dimensions than the conventional OR. For each OR, air samplings were carried out at three different locations; the patients' abdominal cavities, beside the surgical table, and at the exhaust vent, as shown in Fig. 1. The VOCs in the surgical smoke sampled directly from the patients' abdominal cavities provide information on the source strength of the pollutants. The VOC measurements taken beside the surgical table and at the exhaust vent of the ORs provide information on the OR air quality experienced by the surgical staff at different locations. Due to the complexity of the surgeries in hand, and after consultation with the medical staff, the measurements taken in the patients' abdominal cavities were conducted during only two surgeries in a conventional OR and one surgery in a robotic OR. VOCs and other pollutants including CO, CO_2, and TAB in the indoor air of the ORs were simultaneously measured at the exhaust vent during five conventional surgeries and three robotic surgeries to analyze the general indoor air quality in the ORs.

Experimental Setting

The experiments were carried out at the Kyungpook National University Medical Center in Daegu, South Korea. The medical center was newly built in 2011 as a cancer-specialization hospital with 13 ORs. Two of these ORs having different floor areas, were chosen for this study as it

Table 1. Summary of ORs and measurements.

Operation room			No. of surgery	Measurement date
Surgery setting	Dimension	Area of LAF system		
Conventional surgery	6.6 m × 6.6 m × 3 m	4 units × 0.74 m^2 $unit^{-1}$	S1	Aug. 2014
			S2	Aug. 2015
			S3	Aug. 2015
			S4	Aug. 2015
			S5	Feb. 2016
Robotic surgery	10 m × 6.6 m × 3 m	6 units × 0.74 m^2 $unit^{-1}$	S6	Feb. 2015
			S7	Feb. 2015
			S8	Feb. 2015

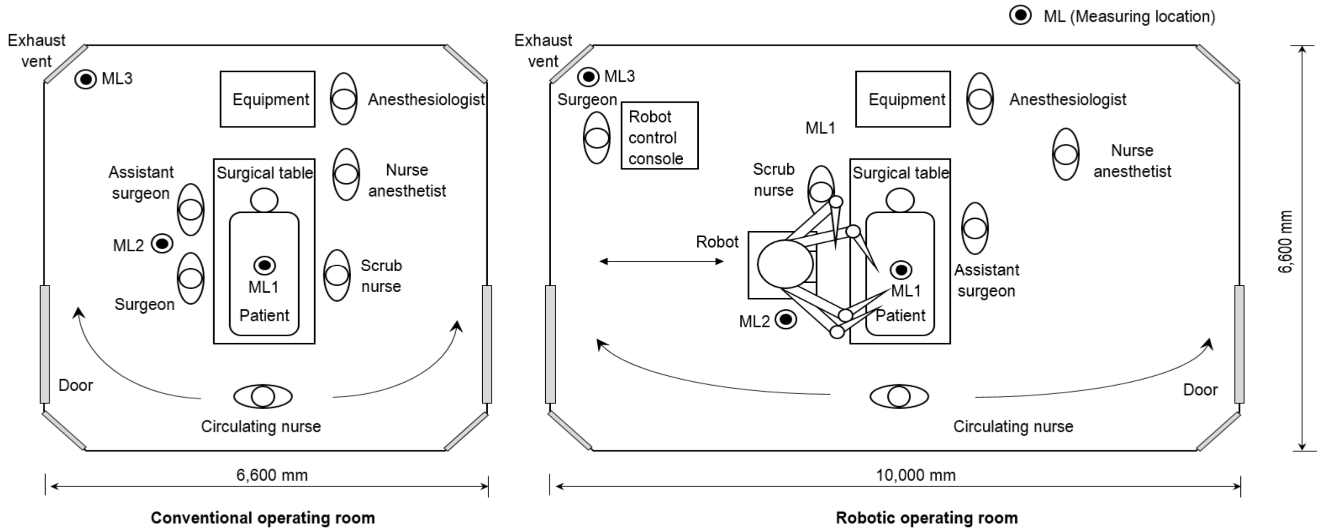

Fig. 1. Plan of operating rooms and measurement locations.

was assumed that the room volume may affect the pollutant distribution. One OR (conventional OR) measured 6.6 m × 6.6 m × 3 m (width × length × height) with conventional surgery setting, while the other OR (robotic OR) measured 10 m × 6.6 m × 3 m (width × length × height) with robotic surgery setting. In addition to the patient, these rooms were staffed by a surgeon, an assistant surgeon, a scrub nurse, an anesthesiologist, a nurse anesthetist, and a circulating nurse. As shown in Fig. 1, in the robotic OR, the surgeon worked at the robot control console in one corner of the room, while in the conventional OR, the surgeon worked immediately over the patient. This difference in the location of the surgeon would result in different exposures to the surgical smoke. The assistant surgeon and scrub nurse stand close to the patient, so that they are more likely to be exposed to the surgical smoke, while the anesthesiologist, nurse anesthetist and circulating nurse would be positioned relatively far from the surgical table. The common surgical equipment present in both rooms consists of the operating table in the center of the room, an anesthesia cart, and extra tables for instruments, including a CO_2 insufflator, an energy source for electrosurgical cutting and coagulation, and an endoscopic camera system. The robotic OR features a surgery robot and a robot control console. The two different types of ORs used different ceiling lamps (a halogen lamp in the conventional OR and a lighting emitting diode (LED) lamp in the robotic OR). An endoscopic light source was used for all of the surgeries addressed by this study, such that the ceiling lamps were actually not needed. Therefore, there would be no air flow disturbances caused by the heat being generated by the different types of lamps.

Each OR was equipped with a ceiling-mounted unidirectional downward laminar air flow (LAF) system with a fan filtered unit (FFU) for ventilating the OR. The LAF system was located directly above the operating table. In the conventional OR, the LAF system consisted of six units × 0.74 m^2 $unit^{-1}$, while in the robotic OR, 4 units × 0.74 m^2 $unit^{-1}$. The FFU uses air filter of class 100,000 certification (US Federal Standard 209E, 1992), which is equivalent to ISO class 5 (ISO EN 14644-4, 1999). Exhaust vents were located at each corner of both ORs. The ventilation systems provided filtered air to the conventional OR at a supply flow rate of 4,500 m^3 h^{-1}, partially recirculating the air at a flow rate of 600 m^3 h^{-1}. For the robotic OR, the supply flow rate was 6,800 m^3 h^{-1}, partially recirculating the air at a flow rate of 1,100 m^3 h^{-1}. The ventilation systems were capable of attaining 20 air changes per hour (ACH) at the total flow rate and 5 ACH at the outdoor air exchange rate, thus satisfying the ASHRAE guideline (ASHRAE, 2008). A positive air pressure was maintained inside each OR relative to that in the adjacent sterile corridor, thus giving rise to an air flow of 290m^3 h^{-1} from the conventional OR and 450 m^3 h^{-1} from the robotic OR.

Air Sampling and Analysis

To measure the VOC concentrations in the surgical smoke inside a patient's abdominal cavity, the Tedlar bag method was used. A 5-liter Tedlar sampling bag was connected to the cannula of a 12-mm bladeless trocar (Ethicon Endo-Surgery Inc., Cincinnati, OH, USA) to directly collect air from the patient's abdominal cavity. Three Tedlar bag air samples were collected for each surgery while the electrocautery devices were being used. Each sampling was done rapidly, taking less than 30 seconds. The patient's abdominal cavity was pressurized to attain a 12-psig differential between the abdominal cavity and the atmosphere, using a CO_2 inflator to provide work space for the surgeon in the abdomen. This also enabled the rapid sampling. After the sample had been collected, the bags were immediately sealed and transported to the laboratory so as to minimize the loss of the air sample. In the laboratory, the air in Tedlar bag was pumped into Tenax TA tubes, and then analyzed using a thermal desorption system (TDS2; Gerstel, USA) combined with a gas chromatograph and mass spectrometer (GC/MS) (Agilent 6890N/5975; Hewlett Packard, USA).

The VOCs in the indoor air in the ORs were measured by using a low-flow sampling pump (MP-Σ30H; SIBATA, Japan) with Tenax TA-filled stainless-steel tubes (SUPELCO,

Table 2. List of air sampling instrument.

Measurement	Model	Range	Accuracy
Temperature	Center 342 (Center, Taiwan)	Detection range : –30°C–70 °C	± 0.7°C
Relative humidity	Center 342 (Center, Taiwan)	Detection range : 5%–98%	± 3%
VOCs	MP-Σ30 (SUPELCO, Japan)	Flow rate range: 0.050–0.500 L min^{-1}	± 5%
Total Airborne Bacteria	MAS 100 eco (Merck, Germany)	Nominal airflow: 100 L min^{-1}	± 4%
Carbon monoxide	TSI 7545 (TSI, USA)	Detection range :0 to 500 ppm	± 3%
Carbon dioxide	TSI 7545 (TSI, USA)	Detection range :0 to 5000 ppm	± 3%

Japan). For each measurement, two sampling pumps were used. A total of six air samples were collected with three sequential air samples per sampling pump. When the electrocautery devices were used and the first surgical smoke was released, the first sampling was conducted and subsequent samplings were performed without any interval. The sampling was conducted at an air flow rate of 0.006 m^3 h^{-1} for 30 minutes. After each sampling was completed, the Tenax TA tubes were sealed, transported to the laboratory, and then analyzed using the same analysis procedure as that described above. The VOCs in the indoor air were collected both beside the surgical table and at the exhaust vents, considering the surgical personnel's positions. The measurements beside the surgical table were taken with aim of analyzing the air quality experienced by the surgeons and scrub nurses who stand next to the patient table. The other measurements taken at the exhaust vent aimed to measure the quality of the air being breathed by the other staff, including the anesthetists, anesthesia nurses, and circulating nurse, who work relatively far from the surgical table. For the measurements taken at the surgical table, we intended to collect air samples at the surgeon's position. However, the strict protocol governing surgical site infection control precluded our collecting samples close to the surgeon. Therefore, an alternative location for the air sampling pump was determined, that being immediately behind the surgeon, which was also outside surgeon's range of movement, so as not to interfere with his/her work.

In addition to the VOC measurements, other major indoor pollutants such as CO and TAB were measured at the exhaust vent. We also monitored CO_2 concentration, which is generally not regarded as being a pollutant but for which the concentration is assumed to be quite high due to its use for abdomen inflation. The concentrations of CO and CO_2 were recorded by TSI 7545 indoor air quality meter (TSI, USA) throughout the surgeries. The TAB levels in the ORs were sampled using a Mas-100 eco air sampler (Merck, Germany). The sampling flow rate was 100 L min^{-1}. The sampled air was impacted onto the surface of agar in Petri dishes. Before placing the Petri dishes on the sampling pod of the sampler, the dishes were sterilized with alcohol. Three air samples were collected for each surgery. After the sampling had been performed, the Petri dishes were immediately transported to the laboratory, incubated at 37°C and 5% CO_2, and then enumerated after 48 hours.

The temperatures and relative humidity were maintained at an average of 22°C and 50%, respectively, for all eight surgeries. The latest ventilation standards for ORs recommend that the temperature and relative humidity be within a range of 20 to 24°C and 20 to 60%, respectively (ASHRAE, 2008; FGI, 2010).

RESULTS

Tables 3 to 5 show the VOC concentrations measured in the patients' abdominal cavities, beside the surgical table, and at the exhaust vents. Among VOCs, aromatic hydrocarbons such as benzene, toluene, ethylbenzene, xylene, and styrene (BTEXS), which are reported to be generated by combustion processes and abundant in the surgical smoke were chosen for the analysis (Weston *et al.*, 2009; Choi *et al.*, 2014). The average, standard deviation, and range showing the maximum and minimum concentrations are shown in the tables for the eight surgeries. In Table 3, guidelines were added to define the BTEXS levels that would have an adverse effects on the health of a person working indoors, and to compare the guidelines with values measured in ORs, especially in the patients' abdominal cavities, which are expected to show high levels of VOCs. The guidelines include values established for continuous exposure (WHO, 2010) as suggested by the World Health Organization (WHO), the inhalation reference concentration (RfC) values (USEPA, 2016) suggested by the United States Environmental Protection Agency (USEPA), and the inhalation reference exposure level (REL) values (CalEPA, 2016) suggested by the California Environmental Protection Agency (CalEPA). The RfC values are estimates of the continuous inhalation exposure of a human population, who are likely to be without risk of deleterious non-cancer-causing-effects over a lifetime, to a chemical compound. The inhalation REL values represent the acute, 8-hour weighted, and chronic risks to the personnel. In addition, the indoor concentrations of the other pollutants including the TAB, CO, and CO_2 are shown in Table 6.

VOC Concentrations in Patients' Abdominal Cavities

The VOC concentrations measured in the patients' abdominal cavities are listed in Table 3. The highest BTEXS compound found in the surgical smoke in the patients' abdominal cavities, regardless of the surgeries, was benzene. This was followed by toluene, ethylbenzene, styrene, and xylene. The average concentrations of BTEXS over the three surgeries were 477 µg m^{-3}, 235 µg m^{-3}, 44 µg m^{-3}, 70 µg m^{-3} for benzene, toluene, ethylbenzene, and styrene, respectively. Xylene was not detected in the abdominal cavities. These results are generally consistent with those of a previous study by Choi *et al.* (2014) in which benzene was the predominant BTEXS compound, present in the highest concentration. The concentrations of benzene for all

Table 3. VOC concentrations measured in patients' abdominal cavities.

VOCs[a]		Surgeries in Conventional OR		Surgeries in Robotic OR	Guidelines		
		S1	S5	S6	Continuous exposure[b]	Inhalation REL[c]	Inhalation RfC[d]
Benzene ($\mu g\ m^{-3}$)	Avg.	1266.4 ± 44.3	32.5 ± 24.1	134.4	No safe level of exposure can be recommended.	27 (A), 3 (8), 3 (C)	30
	Range	1228.3–1315.0	14.4–66.2				
Toluene ($\mu g\ m^{-3}$)	Avg.	632.1 ± 7.4	16.8 ± 7.8	55.7	260	37,000 (A), 300 (C)	5,000
	Range	627.7–640.6	9.9–24.3				
Ethylbenzene ($\mu g\ m^{-3}$)	Avg.	123.1 ± 8.4	2.5 ± 1.3	6.7	-	2,000 (C)	-
	Range	113.5–128.6	1.5–3.4				
Styrene ($\mu g\ m^{-3}$)	Avg.	207.9 ± 12.2	0.1 ± 0.1	2.6	260	21,000 (A), 900 (C)	1,000
	Range	199.3–216.5	0.0–0.2				
Xylene ($\mu g\ m^{-3}$)		N.D.[e]	N.D.	N.D.	-	22,000 (A), 700 (C)	100

a: Three Tedlar bag samples were collected for S1 and S5, while single Tedlar bag sample was collected for S6.
b: Continuous exposure value suggested by WHO.
c: Inhalation Reference Exposure Level (REL) according to REL type by CalEPA (REL types: acute (A), 8-hour (8), chronic (C)).
d: Inhalation Reference Concentration (RfC) for chronic exposure suggested by USEPA.
e: Not detected.

three surgeries were far above the WHO guidelines which indicate that no safe level of exposure can be recommended for benzene, and also exceed the 30 $\mu g\ m^{-3}$ and 3 $\mu g\ m^{-3}$ limits suggested by the RfC and REL values. In the case of Surgery 1, the toluene level also exceeds the 260 $\mu g\ m^{-3}$ WHO guideline for continuous exposure and the 300 $\mu g\ m^{-3}$ chronic REL value. For styrene, the results were close to the WHO guidelines, exhibiting a maximum of 216.5 $\mu g\ m^{-3}$. The levels of all the other VOCs were lower than the guidelines. Surgery 1, performed in the conventional OR, produced highest values for all the BTEXS compounds, exceeding the values measured in surgeries 5 and 6 in the robotic OR. The difference in the BTEXS concentrations according to the surgeries may be attributed to the surgery type, the usage duration and skill of the operator of an energy source device, as well as the patient's constitution.

VOC Concentrations in Operating Rooms

Tables 4 and 5 list the VOC concentrations measured beside the surgical table and at the exhaust vent, thus representing the indoor VOC concentrations at different locations during the surgeries. In the case of Surgery 5, an analysis of the indoor VOCs including BTEXS proved impossible due to sample contamination. Therefore, the indoor VOC concentrations for the case of surgery 5 could not be provided in Tables 4 and 5. The VOC concentrations in the surgical smoke inside a patient's abdominal cavity measured by using Tedlar bag method were provided for all surgery cases including surgery 5 in Table 3. The measurements acquired at the surgical table exhibited a similar trend and values as those obtained at the exhaust vent. The BTEXS compound found in the greatest concentration in the surgical smoke, measured at the surgical table and at the exhaust vent for all surgeries was toluene, followed by xylene, and then ethylbenzene. Unlike the measurements taken in the patients' abdomen, the VOC concentrations measured at the surgical tables and at the exhaust vent exhibited low levels of benzene. In some surgeries, benzene was not detected while styrene was not observed in most of the surgeries. Benzene was the only compound for which the measured level exceeds the WHO guidelines for some surgeries, as well as the 3 $\mu g\ m^{-3}$ chronic REL value in the case of Surgery 1. Other compounds were present only in small amounts relative to the guidelines.

Other Pollutants in Working ORs

The indoor concentrations of TAB, CO, and CO_2 measured in the ORs are presented in Table 6. The average TAB concentration measured during eight surgeries ranged from 4 to 202 CFU m^{-3}. According to the UK HTM 2025, the concentration of TAB in working ORs should be below 180 CFU m^{-3} (NHS Estates, 1994). The TAB concentrations measured for every surgery, except Surgery 1, were low relative to the UK HTM 2025, exhibiting a maximum TAB concentration of 64 CFU m^{-3}. The relatively high concentration measured in Surgery 1 was found to be a result of the FFU air filter requiring replacement at the time of measurement. The CO concentrations during all eight surgeries ranged from 0.00 to 3.10 ppm. Surgeries 2, 3, and 8 produced CO

Table 4. VOC concentrations measured at surgical tables in ORs.

VOCs		Surgeries in Conventional OR				Surgeries in Robotic OR		
		S1	S2	S3	S4	S6	S7	S8
Benzene	Avg.	8.4 ± 0.8	N.D.	N.D.	N.D.	2.0 ± 0.1	1.3 ± 0.0	N.D.
(μg m^{-3})	Range	7.8–9.0	N.D.	N.D.	N.D.	1.8–2.1	1.26–1.26	N.D.
Toluene	Avg.	29.9 ± 3.6	7.7 ± 0.4	5.8 ± 0.0	8.5 ± 0.4	5.0 ± 0.9	6.5 ± 0.3	5.5 ± 5.7
(μg m^{-3})	Range	27.3–32.5	7.5–8.0	5.8–5.8	N.D.	3.7–5.7	6.3–6.7	1.5–9.6
Ethylbenzene	Avg.	8.0 ± 0.6	1.7 ± 0.0	1.5 ± 0.0	1.7 ± 0.1	N.D.	1.4 ± 0.0	1.5 ± 0.0
(μg m^{-3})	Range	7.5–8.4	1.7–1.7	1.5–1.5	1.6–1.7	N.D.	1.4–1.4	1.5–1.5
Styrene	Avg.	1.0 ± 1.4	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
(μg m^{-3})	Range	0.0–3.0	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Xylene	Avg.	19.5 ± 9.8	4.9 ± 0.0	4.3 ± 0.0	4.4 ± 0.3	0.8 ± 0.5	3.5 ± 0.1	2.3 ± 2.8
(μg m^{-3})	Range	12.6–26.4	4.9–4.9	4.3–4.3	4.2–4.6	0.6–1.5	3.4–3.6	0.4–4.3

Table 5. VOC concentrations measured at exhaust vents in ORs.

VOCs		Surgeries in Conventional OR				Surgeries in Robotic OR		
		S1	S2	S3	S4	S6	S7	S8
Benzene	Avg.	8.3 ± 0.3	1.8 ± 0.0	N.D.	1.5 ± 0.0	2.6 ± 0.5	N.D.	N.D.
(μg m^{-3})	Range	7.9–8.7	1.8–1.8	N.D.	1.5–1.5	1.9–3.0	N.D.	N.D.
Toluene	Avg.	31.4 ± 0.8	8.4 ± 0.8	6.6 ± 0.0	10.7 ± 0.3	4.9 ± 1.8	6.2 ± 0.0	6.2 ± 7.1
(μg m^{-3})	Range	30.5–32.4	7.9–8.9	6.56–6.56	10.5–11.0	2.7–7.0	5.7–6.7	1.2–11.3
Ethylbenzene	Avg.	7.8 ± 0.0	1.8 ± 0.1	1.6 ± 0.0	2.2 ± 0.2	N.D.	1.3 ± 0.1	1.9 ± 0.0
(μg m^{-3})	Range	7.9–7.8	1.7–1.9	1.6–1.6	2.0–2.3	N.D.	1.2–1.4	1.9–1.9
Styrene	Avg.	1.9 ± 1.4	0.8 ± 0.0	N.D.	N.D.	N.D.	N.D.	N.D.
(μg m^{-3})	Range	0.0–2.6	0.8–0.8	N.D.	N.D.	N.D.	N.D.	N.D.
Xylene	Avg.	15.9 ± 7.6	5.3 ± 0.3	4.6 ± 0.0	5.7 ± 0.5	0.9 ± 0.6	3.1 ± 0.0	2.5 ± 3.5
(μg m^{-3})	Range	10.5–26.6	5.2–5.5	4.6–4.6	5.4–6.0	0.6–1.8	2.4–3.8	0.0–5.0

Table 6. Indoor environment and other air quality conditions.

Pollutants		Surgeries in Conventional OR					Surgeries in Robotic OR		
		S1	S2	S3	S4	S5	S6	S7	S8
Bacteria	Avg.	136 ± 40	11 ± 8	22 ± 25	44 ± 23	38 ± 12	13 ± 3	19 ± 12	22 ± 14
(CFU m^{-3})	Range	84–202	4–20	4–44	28–60	24–64	8–16	12–32	12–32
Carbon monoxide	Avg.	2.68 ± 0.29	N.D.	0.02 ± 0.07	0.14 ± 0.05	0.40 ± 0.24	0.68 ± 0.11	0.53 ± 0.87	N.D.
(ppm)	Range	2.10–3.10	N.D.	0.00–0.20	0.10–0.20	0.20–0.80	0.30–0.90	0.00–0.90	N.D.
Carbon dioxide	Avg.	1309 ± 259	1121 ± 178	1363 ± 99	1217 ± 231	1409 ± 130	1099 ± 203	911 ± 57	1138 ± 135
(ppm)	Range	707–1686	914–1570	1238–1500	907–1583	1123–2315	644–1492	842–1038	959–1399
Carbon dioxide (m^3) used for abdomen inflation		0.600	0.400	0.332	0.318	0.797	0.595	0.604	0.651

concentrations ranging from 0.05 to 0.12 ppm, which is below the global background concentrations recommended by the WHO. The measurements taken for all the surgeries satisfy the WHO guideline value of 10 ppm for 8-hour time-weighted average exposures. The concentrations of CO_2 ranged from 644 to 2,315 ppm. These values correspond to the combined effect of the CO_2 injected into patients for abdomen inflation and the respiration of the surgical staff. Table 6 lists the amount of CO_2 injected into the patients' abdomens during surgeries.

DISCUSSION

Surgical Smoke as VOC Source

Surgical smoke resulting from the application of laser and electrosurgery technology is considered a potential health risk to both patients and surgical staff (Ball, 2001; Ulmer, 2008). The Occupational Safety and Health Administration (OSHA) reported that about 500,000 OR related personnel including surgeons and nurses are exposed to surgical smoke (OSHA, 2016). Surgeries that are now often performed laparoscopically are of concern because they allow smoke buildup inside a patients' abdominal cavity, resulting in a high exposure risk. Many previous studies have investigated particle characterization in surgical smoke and its infection risks (DesCoteaux *et al.*, 1996; Kunachak *et al.*, 1996; Capizzi *et al.*, 1998; Hughes and Hughes, 1998; Bruske-Hohfeld *et al.*, 2008; Andreasson *et al.*, 2009; Mowbray *et al.*, 2013). However, chemical pollutants such as VOCs in surgical smoke have been addressed by only a few studies

(Al Sahaf *et al.*, 2007; Weston *et al.*, 2009; Hill *et al.*, 2012; Mellor and Hutchinson, 2013; Choi *et al.*, 2014) and their impact on the indoor air is rarely discussed. The results of this study indicated that surgical smoke contain large amounts of VOCs, and also showed that the concentrations of several VOCs such as benzene and toluene exceed concentration guidelines such as those published by the WHO, RfC, and REL. Fig. 2 compares the VOC concentrations in the abdominal cavity as measured in the present study and the previous study undertaken by Choi *et al.* (2014). As both studies were conducted in the same hospital, using identical sampling and analysis methods, a direct comparison was possible. It was found that there are many variations in the measured VOC concentrations depending on the surgeries. This may be ascribed to various factors including surgery, surgeons, and patients. Nevertheless, the results clearly show that the benzene concentration greatly exceeds the guideline levels for the acute, 8-hour weighted, and chronic risks to workers, as well as the continuous inhalation exposure in all experimental cases. We can conclude that surgical smoke should be regarded as a VOC source in OR environment and is capable of affecting the indoor VOC concentration.

Influence of Surgical Smoke on OR IAQ

Although high VOC concentrations were detected in the patients' abdominal cavity, the indoor concentrations were found to be low. Fig. 3 compares the average concentrations of BETXS measured in the patients' abdominal cavities, at the surgical tables, and at the exhaust vents for each of the surgeries addressed by this study. The measured indoor VOC concentrations suggest that the indoor concentration of benzene, which was found to be the predominant compound in surgical smoke, was low or not detected in some cases, both at the surgical table and at the exhaust vent. The indoor toluene concentration also decreased relative to the concentration in the patient abdomen. The ratios of the indoor concentration and abdominal concentration were found to be 0.02 for benzene and 0.03 for toluene. We expected that the VOC concentration measured at the exhaust vents would be low given the ample supply of fresh air by the ventilation system that operates during a surgery. Generally, the ASHRAE standard (2008) suggests a minimum outdoor air exchange rate of 5 air changes per hour for an operating room. In our experiments, the downward laminar air flow system was running with a minimum outdoor air exchange of 5 air changes per hour, thus satisfying the ASHRAE standard. However, the similarly low VOC concentration measured at the surgical table was not expected. We assume that the combined effect of the accumulated VOCs in the patient's abdomen, the thermal buoyancy effect of the surgical plume above the patient, and the air flow disturbance caused by surgical lamp may locally raise the concentrations near the table. It should be noted that the measurement location at the surgical table was immediately behind the surgeon so as not to interfere with the surgeon's work. If the measurements were to be taken adjacent to the surgeon's inhalation zone, the results would probably exhibit a higher concentration closer to the concentration sampled in the patient's abdomen. Even when the vertical downward laminar airflow system is running, air flow disturbances can be caused by the obstacles such as the surgical lamp

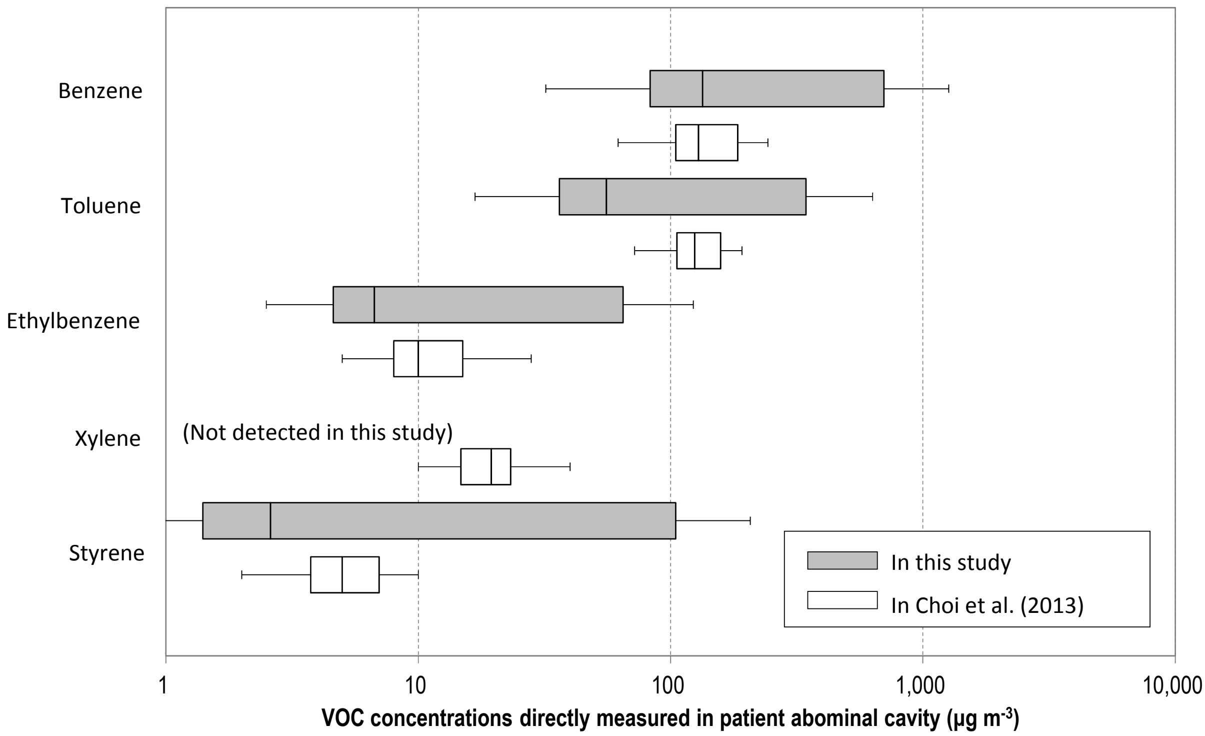

Fig. 2. Comparison of VOC concentrations measured in patients' abdominal cavities obtained in this study and the literature data.

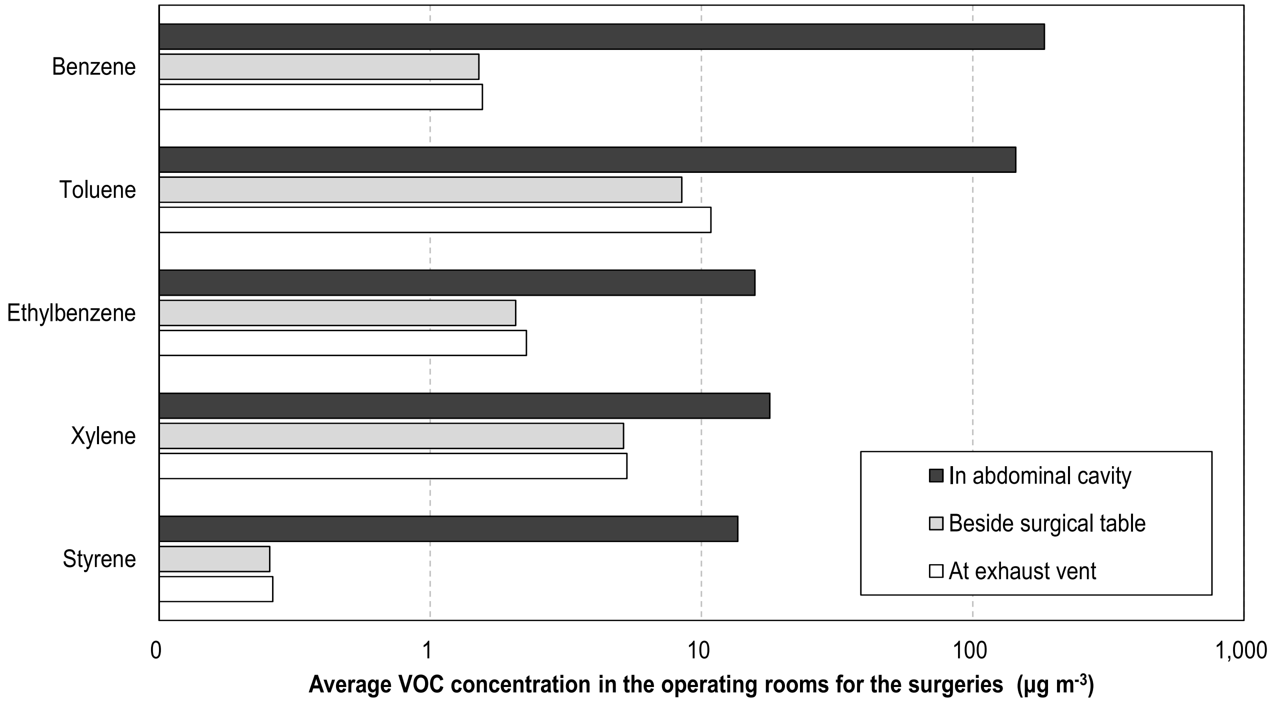

Fig. 3. Comparison of VOC concentrations at three different locations in ORs.

over the table, possibly resulting in the contamination of the surgeon's breathing zone (Chow and Yang, 2003; Chow and Yang, 2005). Moreover, as a surgical plume is generated by the combustion resulting from the use of electrocautery devices, the hot surgical smoke plume can flow upwards, especially when there is a flow disturbance (Chow and Yang, 2003; Liu *et al.*, 2009). In the case of a conventional surgery, where the surgeon is usually standing near or bending towards the patient, the surgeon still be presented with a potential inhalation risk even when the downward ventilation system is running. For a robotic surgeries, the risk of exposure for the surgeon would be reduced due to the change in the location. However, the risk to the surgical staff who are positioned closer to the patient, such as an assistant surgeon and scrub nurse, may increase. Our measurements indicate that most of the surgical staff, such as circulating nurses, anesthetists, and others would not be exposed to smoke with high VOC concentrations. Although the VOC concentrations in the indoor air were lower than those in the abdomen, some VOCs such as benzene were nevertheless found to be a matter of concern, either exceeding or approaching the Cal REL guidelines in some surgeries. The benzene concentration was found to vary depending on the surgery, which can increase the risk of benzene exposure for the surgical staff. To study the influence of surgical smoke at a surgical table, while not interfering with elaborate surgery procedures, mock-up testing or numerical analysis should be considered for further investigation.

New surgical techniques and OR facilities are constantly being developed. Downward ventilation systems were found to be effective in diluting most of the high levels of VOCs. However, depending on the type of surgery, equipment, and OR facility, the trajectory of the VOCs in the OR may vary. Horizontal flow ventilation systems have been proposed as an alternative (Friberg *et al.*, 1998; Liu *et al.*, 2009). At the same time, local smoke evacuation systems equipped with filters have been developed by consensus organizations, and may improve the air quality experienced by the operating staff. As discussed above, laparoscopic surgery, a relatively new technique, generates surgical smoke that is trapped inside the patient's abdomen, causing the surgical staff to experience accumulated VOC concentrations. Robotic surgery, which is rapidly becoming commonplace, changes the position of the surgeon from in front of the patient to a robot control console near the corner of the OR, thereby significantly changing the exposure level of the medical staff. In addition, the OR in which robotic surgery is performed usually requires more space than conventional surgery due to the need to accommodate the robot control station. These changes in the OR space characteristics and additional equipment may have an influence on the air currents in the OR inevitably affecting air quality.

CONCLUSIONS

We investigated the surgical smoke generated during laparoscopic surgery as a VOC source, and its impact on the indoor air quality in a hospital ORs. The VOC concentrations in surgical smoke, measured in patients' abdominal cavities, were compared with the VOC concentrations in the ORs. Simultaneously, VOCs, CO, CO_2 and TAB in an OR were measured to determine the general indoor air quality in the OR. The measurements taken in the patients' abdominal cavities confirmed that the surgical smoke contained high concentrations of VOCs including benzene and toluene, which actually exceed the inhalation health guidelines. A comparison of the measurements taken in the abdominal cavity and in the ORs indicated that the downward laminar air flow system efficiently dilutes the concentration of VOCs to a point below the guideline level. However, the benzene concentration still presents a potential health risk to the surgical staff. The concentrations of CO and CO_2 in the ORs were not notable. The TAB concentrations in the ORs were below the guideline, but the relatively higher TAB concentration in the case of Surgery 1 indicated the importance of FFU filter replacement and management. The present study explored the recently raised issue of surgical smoke and its impact on indoor air quality in terms of chemical composition, including VOCs, and also suggests the need for further research to reveal the local VOC concentration issues at a surgical table. The current study was conducted in the laparoscopic surgical environment in two types of ORs with a downward LAF system. As the influence of the surgical smoke on the indoor air quality in an OR may depend on the surgery types, OR characteristics, and type of ventilation system, a more systematic investigation would allow us to draw a more rigorous conclusion.

ACKNOWLEDGMENTS

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (2015R1C1A1A02037423)

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Received for review, May 9, 2016
Revised, September 11, 2016
Accepted, September 19, 2016