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Chemicals in Surgical Smoke and the Efficiency of Built-in-Filter Ports

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ABSTRACT

Background and Objectives: Surgical smoke contains various malodorous and hazardous combustion byproducts. We aimed to analyze hydrocarbons accumulated in the abdominal cavity during laparoscopic gynecologic surgery and determine the efficiency of a built-in-filter port.

Methods: We prospectively followed seven patients with benign uterine pathology. Surgical smoke was generated using laparoscopic or robotic electrocautery. The smoke was collected twice for each patient using a built-in-filter port and a conventional port. The concentrations of volatile organic compounds and aldehydes were determined using gas chromatography with mass spectrometry and high-performance liquid chromatography with ultraviolet visible light detection and compared using the paired-sample Wilcoxon signed-rank test.

Results: Five volatile organic compounds and five aldehydes had toxic effects or unpleasant odors. The median concentration of formaldehyde before filtration (0.870 ppm) exceeded the time-weighted average concentration (0.75 ppm) of the Occupational Safety and Health Administration. Built-in-filter ports significantly reduced the concentration of five volatile organic compounds and two aldehydes but not that of formaldehyde, acetaldehyde, and propionaldehyde. Formaldehyde concentration decreased by 50% after filtration but remained above the recommended exposure limit (0.016 ppm) of the National Institute of Occupational Safety and Health.

Conclusions: Surgical smoke in minimally invasive gynecologic procedures contains several hazardous hydrocarbons including formaldehyde. Built-in-filter ports have the potential to reduce the exposure of surgical smoke to surgeons and operating room personnel; nevertheless, development of built-in-filter ports is necessary to improve the filtering efficiency for highly concentrated formaldehydes.

Key Words: Volatile organic compounds; Aldehydes; Laparoscopy

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INTRODUCTION

Diathermy is essential during surgery to manipulate tissues and control hemorrhage in the operating field. Electrocautery ablation creates by-products that are usually referred to as surgical smoke; they result from a combination of total and partial incomplete combustion of tissue. Surgical smoke contains large quantities of hydrocarbons, nitriles, fatty acids, and phenols.[1]

The contents of the smoke, including benzene and formaldehyde, are at the very least a nuisance and at worst are carcinogenic.[2] Studies have shown that surgical smoke can cause migraines and irritation and pain in the eyes, nose, and throat; it may be as mutagenic as cigarette smoke.[3,4] Their exposure is regulated by Occupational Safety and Health Administration (OSHA) and the National Institute of Occupational Safety and Health (NIOSH), both of which have recommended exposure limits (RELs) in the working environment regarding the toxicity of various substances.[5,6]

Because laparoscopic surgery is widely accepted in gynecology, the surgical team may have an increased risk of exposure to surgical smoke that densely accumulates in the pneumoperitoneal cavity.[7] Several precautions should be taken to not release smoke and body fluids into the operating room. Health organizations have recommended that evacuation and filtration devices should be routinely used to avoid potential problems associated with smoke exposure.[8] During laparoscopy, the most effective method to eliminate surgical smoke is filtering at the tip of the cannula of a port. The issue of exposure to surgical smoke is not new, and the contents of smoke produced during laparoscopic surgery have been analyzed to identify volatile organic compounds and aldehydes including formaldehyde. Nevertheless, only a few studies have evaluated whether the harmful chemicals can be efficiently reduced or the advantages can be provided by the filtering systems installed on ports.[9–11]

The two objectives of this study were to analyze the concentrations of hydrocarbons in surgical smoke and to determine the efficiency of smoke removal by built-in-filter ports. Therefore, we analyzed hydrocarbons in surgical smoke generated during laparoscopic gynecological surgery with respect to the standards set by health organizations and measured the efficiency of built-in-filter ports in terms of reduction of the concentration.

MATERIALS AND METHODS

We analyzed the chemical composition of surgical smoke and compared the concentration of chemicals in abdominal gases evacuated through a conventional port and a built-in-filter port. This prospective study was performed at a university-affiliated hospital and was approved by the institutional review board. Informed consent was obtained after full discussion.

We prospectively recruited seven patients who underwent laparoscopic or robot-assisted laparoscopic surgery for benign uterine diseases such as leiomyoma or adenomyosis. Patients were placed in the lithotomy position, and four port sites were created, according to surgical approaches of conventional or robot-assisted laparoscopy. A 5-mm port with a filtering system (Tropian Trocar, Tropian Tech, Seoul, Korea) was used to ventilate intra-abdominal gas. Briefly, the filter is composed of two layers of charcoal (1200 m^2/g of surface area) and intervening micropores (1 to 50 μm).

Pneumoperitoneum was created with CO_2, and an insufflator was tuned to maintain intra-abdominal pressure at 12 mm Hg during the procedure. Surgiwand™ (Medtronic, Minneapolis, MN, USA) with a spatula tip or Hot Shears™ EndoWrist cautery (Intuitive Surgical, Sunnyvale, CA, USA) was used for unipolar cautery to cut the uterine specimen during laparoscopic or robotic surgery, respectively. Bleeding vessels were coagulated with unipolar cautery and otherwise bipolar forceps such as Orbitas bipolar forceps (Bissinger, Teningen, Germay) or Maryland bipolar forceps (Intuitive Surgical). The power was set at 35 W using Force FX™ (Medtronic).

Electrocoagulation in cut mode was permitted for 5 minutes before gas sampling for combustion byproducts to reach a sufficient concentration in the intra-abdominal space based on previous studies for surgical smoke generated during laparoscopy.[12,13]

Surgical smoke was collected during myometrial incision for myomectomy and adenomyomectomy or cervical incision for hysterectomy. Nonfiltered gas was drained through a luer-lock valve without a filter and collected in a 10-L Tedlar® bag. Thereafter, the same procedure was repeated, and filtered gas samples were obtained through the filter nozzle.

Each sample was sent for laboratory analysis within 2 hours after gas collection. Quantitative analysis of chemical contents was performed by the Korea Testing and Research Institute (Gimpo, Korea). Volatile organic compounds and aldehydes in gas samples were analyzed using gas chromatography with mass spectrometry and high-performance liquid chromatography with ultraviolet visible light detection (HPLC/UV), respectively. The efficiency (%) of filter was calculated as the removal rate of each chemical as follows, (concentration before filtration − concentration after filtration)/concentration before filtration * 100.

Statistical analysis was performed using SPSS Statistics 24 (IBM, Armonk, NY, USA). The chemical composition of filtered and nonfiltered surgical smoke was compared using the paired-sample Wilcoxon signed-rank test. $P < .05$ was considered statistically significant.

RESULTS

Surgical characteristics are summarized in **Table 1**. Conventional laparoscopic and robot-assisted laparoscopic myomectomy were performed in two patients with uterine leiomyoma. Two patients with uterine adenomyosis underwent total laparoscopic hysterectomy and one underwent laparoscopic focal resection. Only electrocautery was used for cutting and desiccating edges during the procedures, and other instruments such ultrasonic scalpels and lasers were not permitted. A total of 10 chemicals were detected in surgical smoke, including five volatile organic compounds and five aldehydes. Seven chemicals (benzene, toluene, ethyl benzene, xylene, styrene, form-

Table 1.
Patient Characteristics of Laparoscopic Surgery

Case	Age, y	Diagnosis	Surgery
Case 1	41	Adenomyosis	Total laparoscopic hysterectomy
Case 2	39	Leiomyoma	Laparoscopic myomectomy
Case 3	25	Leiomyoma	Robot-assisted laparoscopic myomectomy
Case 4	47	Leiomyoma	Robot-assisted laparoscopic myomectomy
Case 5	38	Adenomyosis	Total laparoscopic hysterectomy
Case 6	32	Adenomyosis	Laparoscopic focal resection
Case 7	45	Leiomyoma	Laparoscopic myomectomy

aldehyde, and acetaldehyde) fell under the purview of standards established by the OSHA and NIOSH (**Table 2**).[7,8] NIOSH has RELs, which are transmitted to OSHA for use in promulgating permissible exposure limits (PELs).[7] A short-term exposure limit is the acceptable average exposure over a short period of time, which is usually 15 minutes. A time-weighted average concentration is defined as the employee's average exposure in any 8-hour (by OSHA) or 10-hour (by NIOSH) work shift of a 40-hour workweek, which shall not be exceeded.

Most chemicals in surgical smoke were below the exposure limits of the NIOSH and OSHA, except formaldehyde (**Table 3**). The median concentration of formaldehyde in surgical smoke before filtration was 0.870 ppm, which was below the short-term exposure limit (2.0 ppm) but exceeded the time-weighted average concentration (0.75 ppm) of PEL of the OSHA. The value was much higher than the RELs of the NIOSH (time-weighted average concentration, 0.016 ppm, short-term exposure limit, 0.1 ppm).

Acetaldehyde and isovaleraldehyde were above the effluent quality standard of odors, even though the health organizations permit higher exposure limits in industrial regions than in others. The median concentration of acetaldehyde in nonfiltered surgical smoke was 0.590 ppm, which was above the PEL for industrial regions (0.1 ppm). The median concentration of isovaleraldehyde (0.015 ppm) also exceeded the PEL for industrial regions (0.006 ppm).

The efficacy of the port with the built-in filter is presented in **Table 3**. The concentrations of seven chemicals in surgical smoke decreased significantly after evacuation through the built-in filter. Nevertheless, levels of three aldehydes (formaldehyde, acetaldehyde, and propionaldehyde) did not significantly decrease after filtration. The filtering system halved the median concentration of formaldehyde (0.450 ppm) and brought it within the PEL of the OSHA, but it remained above the REL of the NIOSH.

DISCUSSION

Five carcinogens (benzene, ethyl benzene, styrene, formaldehyde, and acetaldehyde) were identified in surgical smoke using two analytic methods, gas chromatography for volatile organic compounds and HPLC for aldehydes. Formaldehyde was highly concentrated above the exposure limits of health organizations and could not be eliminated efficiently by built-in filter ports.

Our results were mostly consistent with those of previous studies that reported the composition of surgical smoke.[4] The main components were hydrocarbons and nitriles, with formaldehyde and benzene representing the greatest hazards.[14] Both are not only acutely toxic but are also carcinogenic in humans. In our study, the concentration of hydrocarbons was not negligible but remained within exposure limits, except for formaldehyde.

Formaldehyde is a well-known respiratory irritant and a cause of upper airway diseases, including cancer. Nevertheless, few studies have included formaldehyde in their targets of chemical analyses with surgical smoke. Moss et al.[15] reported high levels of formaldehyde in smoke generated by medical lasers. Air samples were subjected to quantitative measurement using visible absorption spectrophotometry. The peak concentration was between 0.4 and 0.8 ppm, which is above the exposure limits of the American Conference of Governmental Industrial Hygienists (threshold limit value, 0.3 ppm) and OSHA (PEL time-weighted average concentration, 0.75 ppm).[16]

In urologic surgery where minimally invasive surgery has become the norm, one group detected formaldehyde in diathermy gases produced during endoscopic surgery.[17] The gaseous plume collected from transurethral prostate surgery was analyzed using HPLC/UV. Although the level of formaldehyde was less than the threshold (<5.8 ppb), the results suggested the harmful potential of endoscopic surgical smoke because the amount of gases produced during resection was proportional to the resected mass.

In the present study, we detected formaldehyde during laparoscopic surgery. The median concentration was considerably in excess of the time-weighted average concentration PEL of the OSHA and its peak level was around 2

Table 2.
Chemicals Identified in Laparoscopic Surgical Smoke and the Standards of Health Organizations

Chemicals	Exposure Limits (TWA, STEL), ppm	Standard of Odor (Industry, etc.), ppm	Adverse Effects and Odors (ATSDR)
Benzene	REL (0.1, 1)	—	Carcinogen of blood; CNS excitation and depression; Irritation; Blood disorder
	PEL (1, 5)		
Toluene	REL (100, 150)	(30, 10)	CNS depression; Irritation
	PEL (200, 500 [10 min])		Paint, pungent, benzene-like
Ethyl benzene	REL (100, 125)	—	Possible carcinogen; Irritation
	PEL (100, -)		Gasoline-like
Xylene	REL (100, 150)	(2, 1)	Liver enlargement; Narcosis; Anemia; Irritation
	PEL (100, -)		
Styrene	REL (50, 100)	(0.8, 0.4)	Possible carcinogen; CNS depression; Irritation
	PEL (100, 600 [5 min])		Aromatic, sweet, floral, if contains aldehydes: sharp and unpleasant
Formaldehyde	REL (0.016, 0.1 [15 min])	—	Carcinogen of upper airway; Respiratory disease; Irritation
	PEL (0.75, 2)		Pungent, suffocating
Acetaldehyde	PEL (200, —)	(0.1, 0.05)	Possible carcinogen of respiratory system
			Irritation; Narcosis; Pulmonary edema
			Pungent, ethereal, light, airy
Propionaldehyde	—	(0.1, 0.05)	Suffocating, fruity, pungent, unpleasant
Butyraldehyde	—	(0.1, 0.029)	Pungent, cocoa, musty
Isovaleraldehyde	—	(0.006, 0.003)	Pungent, sour

ATSDR, Agency for Toxic Substances and Disease Registry; CNS, central nervous system; PEL, permissible exposure limit of the Occupational Safety and Health Administration; REL, recommended exposure limit of the National Institute for Occupational Safety and Health; STEL, short-time exposure limit; TWA, time-weighted average concentration.

ppm, which is the short-term exposure limit PEL of the OSHA. Considering the size of female genital specimens and the longer duration of procedures,[18] the greater generation of formaldehyde with more extensive use of electrocautery is expected in gynecologic surgery. Exposure to formaldehyde should be of particular concern during laparoscopic surgery involving large specimens.

Unpleasant odors are regarded as warning signs before hazardous chemicals reach the harmful levels. Some suggested odors themselves can cause health symptoms and reduce quality of life and sense of wellbeing.[19] Out of 10 hydrocarbons detected in the surgical smoke, seven (toluene, xylene, styrene, acetaldehyde, propionaldehyde, butyraldehyde, and isovaleraldehyde) are currently controlled by the law of offensive odor control in Korea and Japan.[20,21] Acetaldehyde is a cause of respiratory complaint through its pungent odor at much lower concentration than that of toxicologic standard (**Table 2**). By adding HPLC/UV as one of our analytic methods we could note two aldehydes (acetaldehyde and isovaleraldehyde) were above the standards of odor.

Because smoke is concentrated in the peritoneal cavity, efficient filtering systems are necessary to prevent exposure to surgeons and operating room personnel. Many health organizations, including the NIOSH, have set voluntary guidelines and recommend evacuation and filtration of surgical smoke.[4] In the market several types of filters are available that can be installed or attached to

Table 3.
Reduction of Chemical Concentration (ppm) by Filtering System

Chemicals	Before Filtration		After Filtration		P-Value	Removal Rate, %
	Median	Range	Median	Range		
Benzene	0.050	(0.008–0.085)	0.031	(0.004–0.074)	.018	38.0
Toluene	0.036	(0.005–0.071)	0.011	(0.002–0.029)	.018	69.4
Ethyl benzene	0.009	(0.001–0.029)	0.002	(0.000–0.005)	.018	77.8
Xylene	0.002	(0.001–0.003)	0.000	(0.000–0.001)	.015	100.0
Styrene	0.003	(0.001–0.010)	0.001	(0.000–0.001)	.018	66.7
Formaldehyde*	0.870	(0.020–1.970)	0.430	(0.010–2.130)	.612	50.6
Acetaldehyde†	0.590	(0.070–8.120)	0.450	(0.060–4.600)	.091	23.7
Propionaldehyde	0.020	(0.000–0.230)	0.020	(0.000–0.100)	.109	0.0
Butyraldehyde	0.028	(0.001–0.616)	0.025	(0.001–0.375)	.028	10.7
Isovaleraldehyde†	0.015	(0.000–0.427)	0.012	(0.000–0.278)	.028	20.0

*Above PEL before filtration and REL after filtration.

†Above the standard of odor.

PEL, permissible exposure limit of the Occupational Safety and Health Administration; REL, recommended exposure limit of the National Institute for Occupational Safety and Health.

ports for laparoscopic surgery. Laparoshield™ (Pall, Port Washington, NY, USA) and PlumePort® (ConMed, Largo, FL, USA) are also passive smoke filtration systems using high abdominal pressure to remove surgical smoke. They are highly effective to remove particles and harmful chemicals, as well as to eliminate most of the odor, according to the company's claim. AirSeal® system (ConMed) is an advanced combination of an insufflator, a filtering tube, and a valve-less port. This can evacuate smoke constantly for clear vision and actually reduce overall operative time.[11] Downside of these systems is that they are designed as separate device from the port and require additional steps to connect and use these devices. Therefore, we tested a built-in-filter port, which is expected be well-functioning, feasible, and economical to use.

In our study, the built-in-filter port reduced the concentrations of chemicals in surgical smoke (five volatile organic compounds and two aldehydes), most of which were below the PELs even before filtration. Although the levels of formaldehyde and acetaldehyde tended to be lower, we could not determine whether the reduction occurred by chance. Formaldehyde concentration decreased by 50% (0.870 to 0.430 ppm) and fell below the PEL (0.75 ppm) of the OSHA but not the REL (0.016 ppm) of the NIOSH.

One previous study tested the efficiency of the same port with a disposable built-in filter to eliminate surgical smoke during laparoscopic rectal resection.[9] Five volatile organic compounds and four aldehydes were detected in surgical smoke, and these were filtered in the range of 33%–72%. Nevertheless, the amount of reduction was not significant for most chemicals including formaldehyde (0.22 to 0.13 ppm, $P = .346$).

Recently another group presented improved results using a multilayered complex filter with Luer connector.[10] The amount of carcinogens (1,2-dichloroethane, benzene, and ethylbenzene) removed was more than 85%, and filter performance was maintained after 120 minutes of filtration. Moisture in surgical smoke usually causes loss of flow effectiveness in the filtration device. The multilayered filter included special layers to absorb moisture and prevent malfunction of filtering layers (activated carbon fiber, ultralow particulate air, and antiviral filters).

The built-in-filter port that we tested has a list of benefits (maintenance of peritoneal distension, acceptable price, no need for external system or complicated set-up). Nevertheless, filtering efficiency was rather less than what we expected. The remaining carcinogen levels were not negligible after filtration. Considering the gas was sampled within the initial duration of filtration in our study, filtering ability remains to be improved in addition to moisture management.

There were limitations to our study. First, the number of patients was less in this pilot study. Although the use of ultrasound cutter was avoided to reduce bias, the results should be generalized with caution. Other potential confounders affecting the contents of surgical smoke should have been controlled, such as the incision sites (uterine body for adeno-myomectomy and upper vagina for colpotomy) which are different in histology. Second, targets for analyses were limited (to hydrocarbons) even if biologic particles of surgical smoke were out of our scope which are respirable in size and also potentially hazardous.[22] We selected analysis methods based on the accumulated data regarding combustion by-products and assessed amounts of formaldehyde extracted by a filter using HPLC/UV. Nevertheless, other chemicals generated by electrocautery are receiving attention, including CO and acrylonitrile.[4,12,14,23] Further studies are needed to include more analytical methods to detect a wider range of chemicals and assess the ability of filters to extract those chemicals. Third, the nonfiltered gases were sampled always before the filtered gases. The sampling order could skew the results to have higher concentrations in the nonfiltered gases that may give bias in the efficiency of the filter to the positive direction. More meticulous methods should be addressed in further studies like desufflating the abdomen prior to the collection of both samples.

In conclusion, surgical smoke generated during minimally invasive gynecologic surgery consisted of various volatile organic compounds and aldehydes with toxicity and malodor. Concentrations of formaldehyde were above the exposure limits of health organizations. The built-in-filter port reduced chemical levels by a variety of degrees in this small study. Larger studies are necessary to evaluate the filtration ability and the potential to reduce adverse health effects. Meanwhile we believe that further research and development should enhance the filtering efficiency for the environmental safety of laparoscopic surgical theaters.

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