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Chemical Components of Smoke Produced From Versatile Training Tissue Models Using Electrocautery

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Introduction: While exposure of surgeons and other staff to surgical smoke is an increasing health risk concern, there is a similar risk for users in surgical simulation and training. This study was undertaken to determine the chemical composition of smoke produced from a novel training model, Versatile Training Tissue (VTT), which is used for surgical simulation and training, and to compare this with smoke from a chemosynthetic model and porcine muscle and liver.
Methods: A variety of models (VTT, polyvinyl alcohol, porcine muscle and liver) were prepared and cauterized. Identification of chemical substances in smoke was performed using gas chromatography–mass spectrometry. Quantitative instrumental analysis was implemented with gas chromatography–mass spectrometry and high-performance liquid chromatography. A convenient analysis was performed with a general smoke tube kit.
Results: The main chemical components of smoke produced from VTT models include water and carbon dioxide. A small number of organic compounds were detected. Versatile Training Tissue models produced smoke with fewer compounds than smoke from a chemosynthetic model or porcine muscle.
Conclusions: The concentration of organic compounds from VTT models is considered to be below relevant health risk limits and lower than from polyvinyl alcohol and porcine muscle models. Although porcine liver smoke contains less of the main organic compounds of concern than a KM, it contains potentially hazardous nitrile compounds that are absent in KM smoke. Therefore, surgical simulation and training with VTT models should be considered relatively safe for trainees.
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Key Words: Surgical simulation, surgical smoke, surgical training model.

Much attention has been given to the health effects of surgical smoke on surgeons and other staff during surgical procedures not only in open surgery[1] but also in laparoscopic surgery,[2] thoracoscopic surgery,[3] and robotic surgery.[4] It is said that surgical smoke consists of 95% water or steam and 5% cellular debris in the form of particles. The particles include chemicals, blood, viruses, and bacteria.[5] The chemical components of surgical smoke have been reported.[6] Several chemicals, such as benzene, with a known risk to health have been reported to be in surgical smoke.

In surgical simulation and education, users sometimes use alternate materials, such as chemosynthetic models,[7] animal model, and cadavers.[8] Whatever energy device (eg, electrocautery or ultrasonic scalpel) is applied in the procedure, there is a possibility of the production of smoke from models and potential for health risks by users being exposed to potentially harmful organic compounds. It was reported that toxic compounds (eg, acrylamide, acetaldehyde, formaldehyde, and benzene) are present in surgical smoke with the use of electrocautery and ultrasonic scalpels in a porcine meat model.[9]

In this study, we focused on konjac models [KMs, Versatile Training Tissue models (VTT); KOTOBUKI Medical, Inc, Yashio, Japan], which are used for surgical simulation and training and are made of edible ingredients. KOTOBUKI Medical, Inc, developed these models to solve the issues surrounding the use of animals for surgical training. Because these models are not made of chemical synthetics, it is expected that they have the potential to produce less harmful smoke during training than other chemosynthetic models. The aims of this study were to evaluate the chemical composition of smoke produced during surgical training using energy devices and to compare the composition of smoke produced from a KM with that from a chemosynthetic model and porcine muscle and liver.

METHODS
Materials
Konjac flour and calcium hydroxide were obtained (Moteki Foods Engineering Co, Ltd, Gumma, Japan) and used as raw materials to make a KM. Color paint (Pentel Co, Ltd, Tokyo, Japan) was used to dye the models. Polyvinyl alcohol (PVA) was obtained (Kuraray Co, Tokyo, Japan) and used as a raw material for PVA models. Commercial specimens of porcine tissue (muscle and liver) and salt were purchased.

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KOTOBUKI Medical, Inc, freely provided Versatile Training Tissue to the authors for their research.

Ethics committee approval and informed consent were not required for this study.

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29
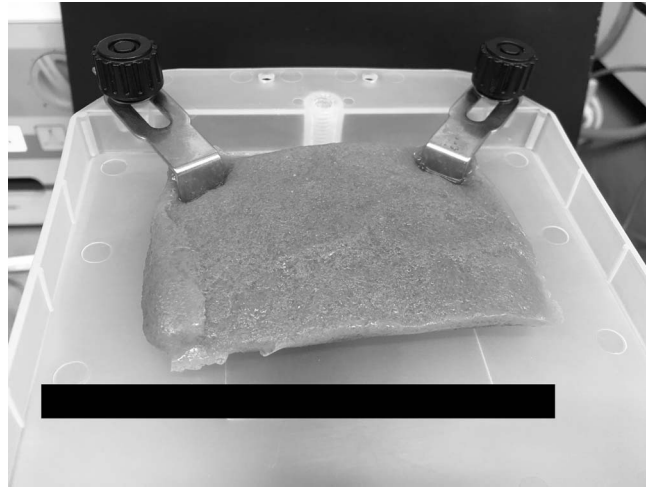
FIGURE 1. A photograph of a KM (scale bar: 10 cm).

Preparation of Models

Four models were tested including a KM, a PVA model, and porcine muscle and liver. Konjac powder, salt, and color paint were dissolved in tap water, and calcium hydroxide was added to obtain konjac paste. This paste was kept in a low temperature environment (−10°C) for at least 30 minutes. After this, the shaped model is dried to create a KM (8 × 5 × 1 cm, approximately 50 g). The shaped KM is shown in Figure 1. Polyvinyl alcohol (39 g), salt (1 g), and color paint (0.5 g) were added to tap water (300 mL). The mixture was put in a microwave oven (500 W) for 5 minutes, and a colored PVA solution was obtained. This was kept at room temperature for 3 hours and then at −10°C at least 12 hours. It was then kept at 15°C for 12 hours and a PVA model obtained (8 × 5 × 1 cm, approximately 50 g; see Figure,

Supplemental Digital Content 1, http://links.lww.com/SIH/A667, which shows the shaped PVA). Porcine muscle and liver (fresh, 15 × 10 × 3 cm, approximately 100 g; see Figure, Supplemental Digital Content 2, http://links.lww.com/SIH/A668, which shows the shaped porcine muscle and liver, respectively; see Figure, Supplemental Digital Content 3, http://links.lww.com/SIH/A669, which shows the shaped porcine muscle and liver, respectively) were used as the third and fourth types of models tested.

Component Identification of Smoke From Models With Simulated Pyrolysis

Pyrolysis of 4 models was done using a pyrolyzer (PY3030D; Frontier Laboratories Ltd, Fukushima, Japan). Each model was cut into a section (1 × 1 cm), and a piece of each model was
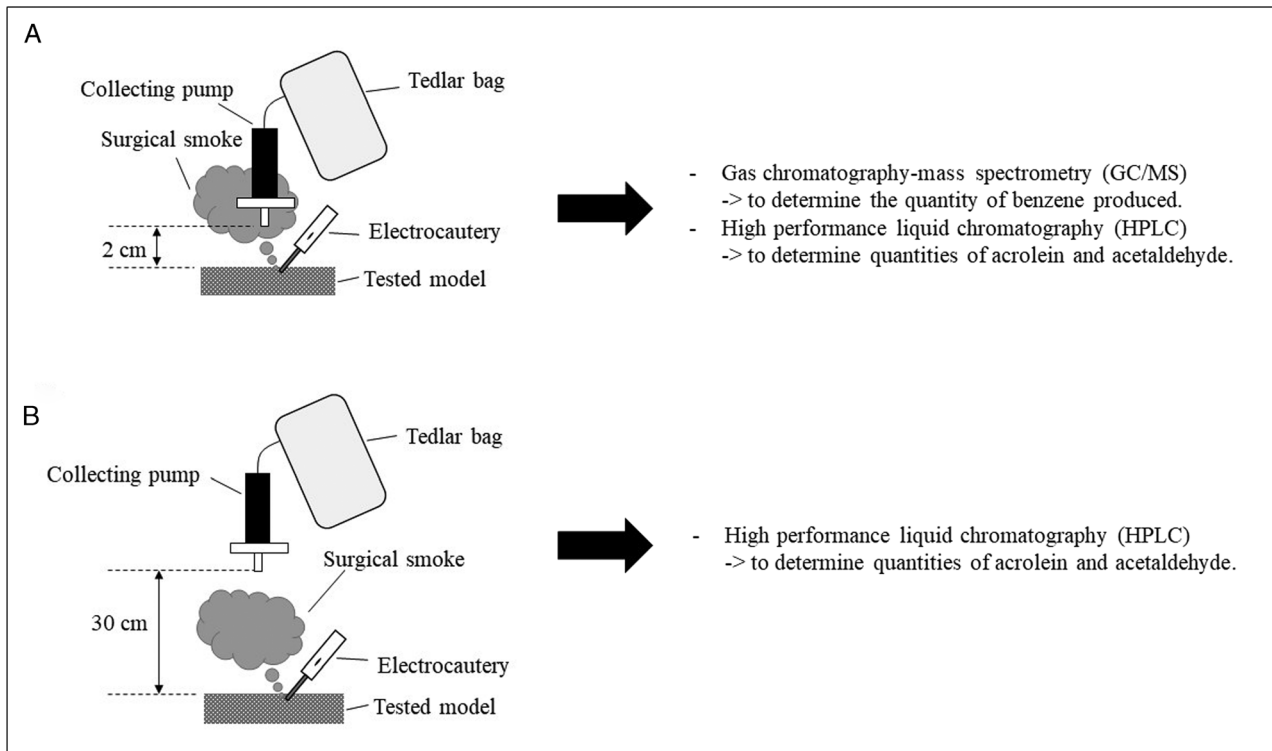
FIGURE 2. Schematic diagram of the procedure for collecting surgical smoke for HPLC and GC/MS at distances of (A) 2 cm and (B) 30 cm.
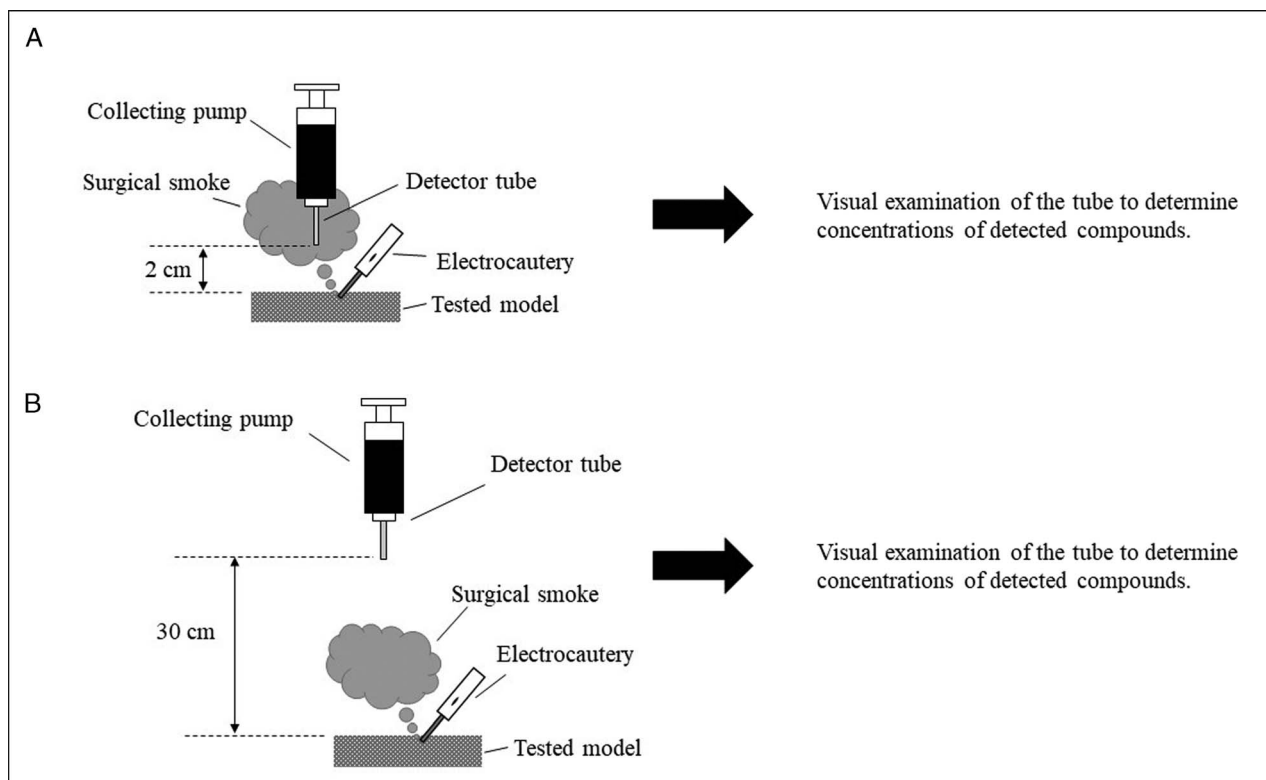
FIGURE 3. Schematic diagram of the procedure for collecting surgical smoke for organic compound detector tubes at distances of (A) 2 cm and (B) 30 cm.

placed in the furnace of the pyrolyzer. The furnace was heated to 800°C for 1 second, and the emitted smoke was collected. Gas chromatography–mass spectrometry (GC/MS; Agilent Technologies 7890B GC System, CA) was used to identify the compounds in the smoke.

Quantitative Instrument Analysis of Smoke From a KM When Using Electrocautery

Electrocautery (Martin ME 401; Martin Medizin-Technik, Tuttlingen, Germany) was used to cut a KM, using cut mode at 30 W. The resulting smoke was collected in a 5-L Tedlar bag at
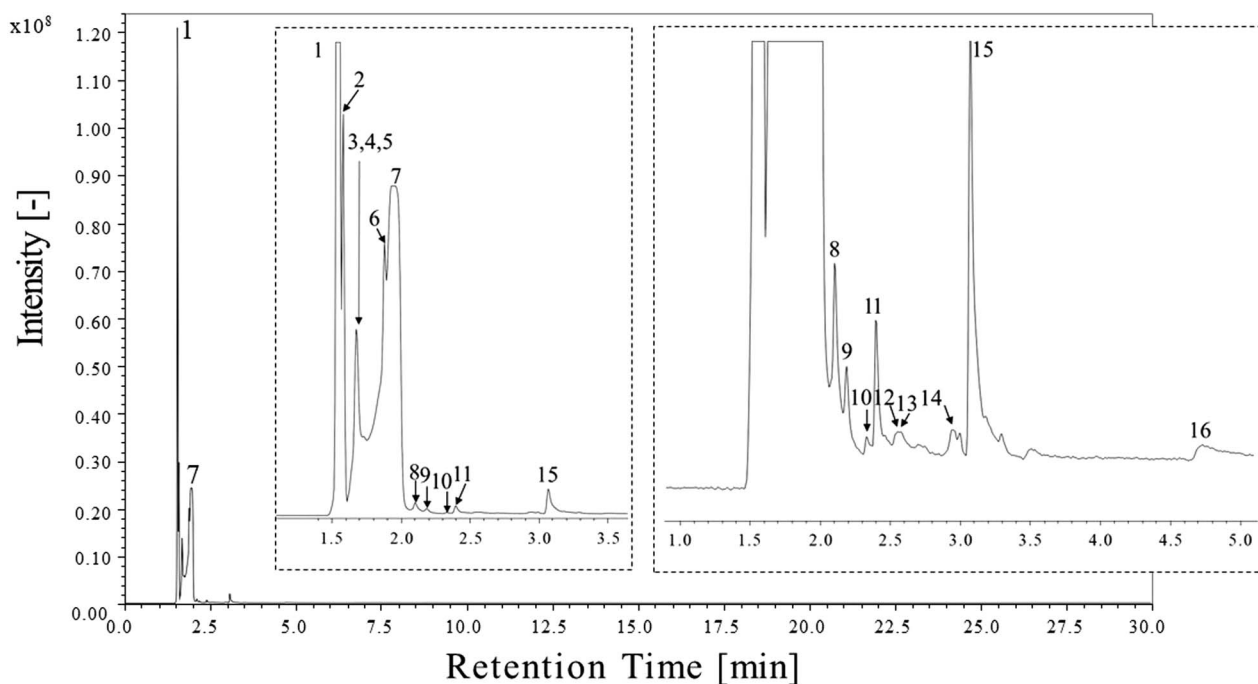
FIGURE 4. Gas chromatographic profile obtained from smoke produced by pyrolyzing a KM. The identification of peaks is shown in Table 1.

TABLE 1. Gas Chromatography–Mass Spectrometry Identification and Peak Area Contribution (Percent) of Compounds Found in Smoke From a KM

Peak	Retention Time, min	Compound	Normalized Areas, %
1	1.54	Carbon dioxide	44.4
2	1.58	Propene	8.3
3	1.67	Acetaldehyde	1.2
4	1.68	1-Butene	1.8
5	1.68	1,3-Butadiene	1.6
6	1.88	2-Propenal	10.7
7	1.94	Water	31.8
8	2.10	1,3-Cyclopentadiene	0.2
9	2.19	Cyclopentene	0.1
10	2.33	2-Butenal	0.0
11	2.40	1-Hexene	0.2
12	2.56	2-Methylfuran	0.0
13	2.58	Cyclopentene, 3-methyl	0.0
14	2.94	1,4-Cyclohexadiene	0.0
15	3.07	Benzene	1.1
16	4.73	Toluene	0.2

distances of 2 and 30 cm (Fig. 2). Gas chromatography–mass spectrometry (Agilent Technologies 7890B GC System) was used to determine the quantity of benzene produced. High-performance liquid chromatography (HPLC; Hitachi High Technologies Chromaster, Tokyo, Japan) was used to determine quantities of acrolein and acetaldehyde.

Comparison of Organic Compounds Produced When Performing Convenient Analysis

The electrocautery in cut mode was used at 30 W. After cutting part of a model for 20 seconds, the smoke was collected with a collecting pump (Gastec AP-20) at distances of 2 and 30 cm (Fig. 3). Concentrations of benzene, 1,3-butadiene, acrolein, and acetaldehyde were measured by detector tubes (Kitagawa, type nos. 118SD, 168SE, 136, and 133SB, respectively; Komyo Rikagaku Kogyo K. K., Kanagawa, Japan).

Ethics committee approval and informed consent were not required for this study.

RESULTS

Smoke from each model was analyzed using GC/MS. The gas chromatograms are shown in Figure 4 for the 6 models and lists of identified compounds in Table 1. Focusing on KMs (Fig. 4 and Table 1), 1 of the 2 major peaks in Figure 4 (*a*) at a retention time of 1.54 minutes (1) is carbon dioxide and the other at 1.94 minutes (7) is for water. Other compounds that might be overlapped by the major peaks are shown in Figure 4, such as acetaldehyde (3), 1,3-butadiene (5), acrolein (2-propenal, 6), and benzene (15). We obtained a chromatogram for a PVA model (see Figure, Supplemental Digital Content 4, http://links.lww.com/SIH/A670, which shows a chromatogram for a PVA model). As there are 2 major peaks at 1.45 minutes (1) and 1.76 minutes (4) referring to the GC/MS identification result (see Table, Supplemental Digital Content 7, http://links.lww.com/SIH/A673, which demonstrates GC/MS identification and peak area contribution of compounds found in smoke from PVA, carbon dioxide and water, respectively), the outline is similar to that obtained with a KM. Chromatograms for porcine muscle and liver were obtained (see Figure, Supplemental Digital Content 5, http://links.lww.com/SIH/A671, which shows a chromatogram for porcine muscle and liver, respectively; see Figure, Supplemental Digital Content 6, http://links.lww.com/SIH/A672, which shows a chromatogram for porcine muscle and liver, respectively). Although these major peaks are for water and carbon dioxide, some nitrile compound are included in the chromatograms and compound list (see Table, Supplemental Digital Content 8, http://links.lww.com/SIH/A674, which demonstrates GC/MS identification and peak area contribution of compounds found in smoke from porcine muscle and liver, respectively; see Table, Supplemental

TABLE 2. Organic Compounds in Smoke From a KM Using Electrocautery (Cutting Mode, 30 W)

	Exposure Limits (TWA, STEL), ppm	Organic Compounds Concentration, ppm (v/v)	
		2-cm Distance	30-cm Distance
A. HPLC analysis			
Acrolein	REL (0.1, 0.3)	3.4	0.048
	PEL (0.1, —)		
Acetaldehyde		22	n.d.
	PEL (200, —)		
B. GC/MS analysis			
Benzene	REL (0.1, 1)	0.12	n.d.
	PEL (1, 5)		

n.d., not determined; PEL, permissible exposure limit; REL, recommended exposure limit; TWA, time-weighted average concentration.

TABLE 3. Organic Compounds in Smoke From Models Produced by Using Electrocautery (Cutting Mode, 30 W)

	Exposure Limits (TWA, STEL), ppm	Organic Compounds Concentration, ppm (v/v)							
		2-cm Distance				30-cm Distance			
		KM	PVA Gel	Porcine Muscle	Porcine Liver	KM	PVA Gel	Porcine Muscle	Porcine Liver
Acrolein	REL (0.1, 0.3)	<50	7000	200	<50	<50	n.d.	n.d.	n.d.
	PEL (0.1, —)								
Acetaldehyde		15	>140	30	<5	<5	n.d.	n.d.	n.d.
	PEL (200, —)								
Benzene	REL (0.1, 1)	<0.2	n.d.	n.d.	n.d.	<0.2	n.d.	n.d.	n.d.
	PEL (1, 5)								
1,3-Butadiene	PEL (1, 5)	4.5	>10	9	2	0.6	n.d.	n.d.	n.d.

<, limit of the sensing method; >, over the measuring range; n.d., not determined; PEL, permissible exposure limit; REL, recommended exposure limits; TWA, time-weighted average concentration.

Digital Content 9, http://links.lww.com/SIH/A675, which demonstrates GC/MS identification and peak area contribution of compounds found in smoke from porcine muscle and liver, respectively).

The quantitative instrumental analysis of smoke from a KM is shown in Table 2. When the distance from the KM to the collector bag was 2 cm, which represents a worst-case scenario for exposure of an operator, the concentrations of acetaldehyde (22 ppm; Table 2A) and benzene (0.12 ppm; Table 2B) are lower than permissible short-time exposure limit (STEL) according to the Occupational Safety and Health Administration. However, the level of acrolein (3.4 ppm) exceeded the National Institute of the Occupational Safety and Health recommended STEL of 0.3 ppm (Table 2A) at this distance. The concentration of acrolein decreased to 0.048 ppm at a sampling distance of 30 cm, which may more closely represent the distance between an operator's face and the source of smoke.

For comparison, a convenient analysis using PVA and porcine models was carried out under the same sampling conditions. The results show that the concentration of 2 types of organic compounds in smoke generated from cutting the PVA gel was much higher than the other models (KM and porcine tissue; Table 3). In contrast, the concentration of chemicals in smoke from KMs is lower than that from PVA gel and porcine muscle models and slightly higher than porcine liver.

DISCUSSION

The toxic effects of surgical smoke on operating room personnel may be a threat even for surgical education. The chemical substances in smoke produced by the use of electrocautery on surgical simulation models have not been evaluated. In this study, we focused on a KM that is used to make models made of edible ingredients. We evaluated the components of smoke produced from a KM, PVA, porcine muscle, and liver with simulated pyrolysis. We carried out component identification of smoke produced from a KM with electrocautery and compared this smoke with smoke produced by other models made of other ingredients. The 2 major peaks in the gas chromatograms of all 4 materials corresponded to water and carbon dioxide, which is reasonable considering that the KM and PVA samples are water-based polysaccharide and PVA gels, respectively, and muscle and liver are predominantly water and protein. This suggests that the visible white smoke generated when cutting or coagulating these models with the electrocautery mainly consists of steam (the carbon dioxide being invisible).

The concentrations of organic compounds in the KM smoke were below relevant health risks and lower than in the smoke generated from PVA and porcine muscle. Although the main organic components of smoke from a KM and PVA were carbon hydride and aldehyde, some additional nitrile compounds were detected in smoke from porcine muscle and liver. Acetonitrile, in particular, has been reported as a nasal irritant and throat asphyxiant and has caused liver and kidney damage in animal models.[10]

The quantitative instrument analysis of smoke from a KM suggests that the concentration of organic compounds decreases with greater distance from the source of surgical smoke when using the electrocautery. This seems intuitive, and it agrees with the previous study[11] and is the basis of important advice that operators maintain as great a distance as possible when using the electrocautery with this model. Although the effect of distance from the source of surgical smoke on the concentration of chemicals for all the model except for a KM was not be analyzed, it should decrease as the distance increases.

In comparison, it was found that the concentration of organic compounds in smoke from a KM is lower than in smoke from PVA gel and porcine muscle. These compounds include benzene, acetaldehyde, and acrolein. Benzene is classified as a carcinogen in humans, and exposure to the compound might result in leukemia.[12] Acetaldehyde may cause erythema, coughing, pulmonary edema, and narcosis.[10] Acrolein may have the risk for causing eye, skin, and upper respiratory tract irritant. It may increase blood clotting time and cause liver and kidney damage.[10] It has been reported that locally high temperatures in body tissue can cause pyrolysis and then surgical smoke containing organic compounds is generated.[13,14] Contrary to this, in the case of a KM, which is cauterized at a high temperature, the possible occurrence of such pyrolysis is probably less than in body tissue because a KM does not contain fat or protein but is a gel made from a plant-derived polysaccharide (hemicellulose), konjac. In the experiment with the PVA model and porcine muscle, existing organic compounds (such as acrolein, acetaldehyde, and 1,3-butadiene) with relatively high concentrations in the smoke are confirmed despite not being detected in gas chromatogram (see Table, Supplemental Digital Contents 7, http://links.lww.com/SIH/A673 and 8, http://links.lww.com/SIH/A674, which demonstrate GC/MS

identification and peak area contribution of compounds found in smoke from PVA and porcine muscle, respectively). As the peak positions close to each other, the peaks of acrolein/1,3-butadiene and acetaldehyde were considered to be overlapped by the water and carbon dioxide peaks, respectively.

We emphasize that these results do not estimate the real danger to operators who use the electrocautery. However, these results suggest that a KM may result in a lower risk of exposure to harmful organic compounds derived from surgical smoke than from models made of PVA and porcine muscle as a surgical training model. From the results of this study, it is recommended that users choose relatively safe models, maintain as much distance as possible, and ventilate the room when using electrocautery in surgical simulation and education.

REFERENCES

1. Rimmer V. Diathermy smoke plume: why do we put up with it? *J Perioper Pract* 2009;29:424–427.

2. Choi S, Kwon T, Chung S, Kim TH. Surgical smoke may be a biohazard to surgeons performing laparoscopic surgery. *Surg Endosc* 2014;28:2374–2380.

3. Rakovich G, Urbanowicz R, Issa R, Wang HT. Minimizing the risk of aerosol contamination during elective lung resection surgery. *Ann Surg* 2020;272:125–128.

4. Eynde JV, Groote SD, Lerberghe RV, Eynde RV, Oosterlinck W. Cardiothracic robotic assisted surgery in time of COVID-19. *J Robot Surg* 2020;14:795–797.

5. Gonzalez-Bayon L, González-Moreno S, Ortega-Perez G. Safety considerations for operating room personnel during hyperthermic intraoperative intraperitoneal chemotherapy perfusion. *Eur J Surg Oncol* 2006;32:619–624.

6. Barrett WL, Garber SM. Surgical smoke—a review of the literature. *Surg Endosc* 2003;17:979–987.

7. Hassan S, Eisma R, Malhas A, Soames R, Harry L. Surgical simulation flexor tendon repair using Thiel cadavers: a comparison with formalin embalmed cadavers and porcine models. *J Hand Surg Eur* 2015;40:246–249.

8. Milad MP, Alvi FA, Breen MT, Brincat C. Laparoscopic major vascular injury simulation using a synthetic compared with porcine model. *Obstet Gynecol* 2017;130:24S–28S.

9. Krones CJ, Conze J, Hoelzl F, Stumpf M, Klinge U. Chemical composition of surgical smoke produced by electrocautery, harmonic scalpel and argon beaming—a short study. *Eur Surg* 2006;39:118–121.

10. Ulmer BC. The hazards of surgical smoke. *AORN J* 2008;87:721–734.

11. Wang HK, Mo F, Ma CG, et al. Evaluation of fine particles in surgical smoke from an urologist's operating room by time and by distance. *Int Urol Nephrol* 2015;47:1671–1678.

12. Dobrogowski M, Wesolowski W, Kucharska M, et al. Health risk to medical personnel of surgical smoke produced during laparoscopic surgery. *Int J Occup Med Environ Health* 2015;28:831–840.

13. Dobrogowski M, Wesolowski W, Kucharska M, Sapota A, Pomorski LS. Chemical composition of surgical smoke formed in the abdominal cavity during laparoscopic cholecystectomy -assessment of the risk to the patient. *Int J Occup Med Environ Health* 2014;27:314–325.

14. Gatti JE, Bryant CJ, Noone RB, Murphy JB. The mutagenicity of electrocautery smoke. *Plast Reconstr Surg* 1992;89:781–784.