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Quantitative Chemical Analysis of Surgical Smoke Generated During Laparoscopic Surgery With a Vessel-Sealing Device

Michele Gianella, DSc[1], Dieter Hahnloser, MD[2], Julien M. Rey, DSc[1] and Markus W. Sigrist, DSc[1]

Abstract

Background. Exposure to surgical smoke in the operation room has been a long-standing concern. Smoke generated by the interaction between lasers or electrocautery devices with biological tissue contains several toxic and carcinogenic substances, but only a few studies so far have provided quantitative data necessary for risk assessment. *Methods*. With laser and Fourier-transform infrared spectroscopy, we investigated the chemical composition of smoke produced with a vessel-sealing device in an anoxic environment during laparoscopic surgery. *Results*. Harmless concentrations of methane (<34 ppm), ethane (<2 ppm), and ethylene (<10 ppm) were detected. Traces of carbon monoxide (<3.2 ppm) and of the anesthetic sevoflurane (<450 ppm) were also found. *Conclusions*. Gas leaking or gas being released from the pneumoperitoneum could therefore increase pollution by waste anesthetic gas in the operating room. Most toxic compounds found in earlier studies remained undetected. Adverse health effects for operating room personnel due to some of those substances (eg, toluene, styrene, xylene) can be excluded, assuming no significant losses or changes in the chemical composition of the samples occurred between our sampling and measurements.

Keywords

colorectal surgery, surgical smoke, chemical analysis, infrared spectroscopy

Introduction

The purpose of this study was to determine the quantitative chemical composition of surgical smoke produced by a vessel-sealing device during laparoscopic surgery, with the objective of establishing the health hazard for operation room (OR) personnel and patients caused by exposure to surgical smoke.

Surgical smoke refers to gases, vapors, biological matter, and particulate matter released as a by-product of the use of heat-generating surgical equipment.[1,2] Devices known to generate surgical smoke include lasers, bone drills, saws and burrs, and high-frequency electroknives.

Apart from the unpleasant odor, surgical smoke has been shown to be a viable transmission mechanism for the human papillomavirus.[3,4] Laboratory experiments have also shown the presence of blood aerosol in the plume generated by bone saws, drills, and electrocautery equipment.[5,6] Several studies have found a multitude of chemical compounds, many of which are toxic, and the mutagenicity of surgical smoke has been compared to that of cigarette smoke.[7] A selection of detected substances and references are listed in Table 1. Apart from few exceptions,[8-11] quantitative information is often not available, which makes it impossible to assess the risk caused by the exposure of OR personnel to surgical smoke.

Many countries set exposure limits for numerous chemical compounds to safeguard the health of workers. These limits are usually given as time-weighted average (TWA) concentrations over a 10-hour workday (United States[29]) or an 8-hour workday (Switzerland[30]) and assuming a 40-hour workweek. For some compounds, there are also short-term exposure limits (eg, TWA concentrations over 15 minutes). Ceiling concentrations that should never be exceeded and concentrations that pose an

[1]Institute for Quantum Electronics, ETH Zürich, Zurich, Switzerland
[2]UniversitätsSpital Zürich, Zurich, Switzerland

Corresponding Author:
Markus W. Sigrist, Institute for Quantum Electronics, ETH Zurich, Schafmattstrasse 16, CH-8093 Zurich, Switzerland.
Email: sigristm@phys.ethz.ch

Table 1. List of Chemical Compounds Detected in Surgical Smoke in Previous Studies.

Name	CAS No.	References	Name	CAS No.	References
Toluene	108-88-3	1, 10-25	Pentadecane	629-62-9	10, 13
Ethylbenzene	100-41-4	1, 10, 11, 13-17, 19-25	Tetradecane	629-59-4	10, 20
Styrene	100-42-5	1, 11, 13-18, 23-25	Decane	124-18-5	10, 20
Benzene	71-43-2	1, 11, 13-19	Formaldehyde	50-00-0	1, 11
Acrylonitrile	107-13-1	1, 11, 16, 18, 22, 23, 26	1-Butene	106-98-9	1, 11
1-Undecene	821-95-4	1, 10, 13, 15, 20, 21	Acetone	67-64-1	11, 15
1-Decene	872-05-9	1, 10, 12, 13, 15, 21	1-Pentene	109-67-1	11, 26
p-Xylene	106-42-3	10, 11, 13, 15, 20	Heptanal	111-71-7	10
m-Xylene	108-38-3	10, 11, 13, 15, 20	Nonanal	124-19-6	10
Carbon monoxide	630-08-0	1, 11, 17, 27, 28	Cyclohexanone	108-94-1	10
Furfural	98-01-1	1, 12, 15, 20, 21	Perchloroethylene	127-18-4	10
Propanenitrile	107-12-0	12, 18, 22, 23	Tridecane	629-50-5	10
Hydrogen cyanide	74-90-8	1, 8, 17, 28	Ammonia	7664-41-7	12
Propylbenzene	103-65-1	10, 13, 15, 20	1-Hexene	592-41-6	11
Isobutene	115-11-7	1, 12, 18, 26	Isooctane	540-84-1	11
1-Heptene	592-76-7	11, 12, 13, 15	Propadiene	463-49-0	26
1,3-Butadiene	106-99-0	1, 8, 12, 26	Vinylacetylene	689-97-4	26
Propene	115-07-1	1, 11, 18, 26	Mercaptomethane	74-93-1	26
Ethylene	74-85-1	1, 12, 18	Ethylacetylene	107-00-6	26
Methylthiocyanate	556-64-9	12, 13, 15	Diacetylene	460-12-8	26
1-Dodecene	112-41-4	10, 13, 15	Ethanol	64-17-5	26
1-Tetradecene	1120-36-1	10, 13, 15	Piperylene	540-60-9	26
Acetylene	74-86-2	1, 8, 18	Propenylacetylene	2206-23-7	26
o-Xylene	95-47-6	10, 11, 13	1,4-Pentadiene	591-93-5	26
3-Methylstyrene	100-80-1	12, 20	Cyclopentadiene	542-92-7	26
1-Dodecane	112-40-3	10, 20	Butyrolactone	96-48-0	26
1-Undecane	1120-21-4	10, 20			

immediate danger to life or health are also given occasionally. As an example, consider carbon monoxide: The recommended exposure limit by the US National Institute for Occupational Safety and Health (NIOSH) is 35 ppm (10-hour TWA), with a ceiling of 200 ppm and an immediate danger to life or health concentration of 1200 ppm.[29] In Switzerland, the recommended exposure limit (maximale Arbeitsplatzkonzentration or MAK) for carbon monoxide is 30 ppm (8-hour TWA); the short-term exposure limit is also 30 ppm (15-minute TWA).[30]

Although unrelated to surgical smoke, exposure to waste anesthetic gases represents another potential health hazard. Waste anesthetic gas pollution in hospitals is an extensively discussed topic in the literature.[31-49] The use of gaseous (nitrous oxide) and volatile anesthetics (sevoflurane, isoflurane, desflurane, etc) inevitably results in some degree of pollution of the air in the OR. Waste anesthetic gas pollution is linked to gas leakage from the patient's mask, from endotracheal coupling, from loose tube fittings, and from air exhaled by patients in the recovery room after surgery.[50] It is not clear what effect long-term exposure to low concentrations of volatile anesthetics has, but experiments on animals have shown adverse health effects.[51,52] As a precaution, NIOSH recommended in 1977 exposure limits for all halogenated anesthetics.[53]

Methods

To investigate the chemical composition of surgical smoke, a total of 31 gas samples were collected during 6 laparoscopic colorectal resections (Table 2). The CO_2 pneumoperitoneum pressure was kept at 12 mm Hg (16 mbar) in all operations. The operations took place between June 2009 and September 2010 at the University Hospital Zurich, Switzerland. A vessel-sealing device (LigaSure, Covidien AG Schweiz, Wollerau, Switzerland) was used to dissect and cut the tissue. In its bipolar operation mode, a high-frequency voltage is applied between the 2 electrodes of the device. A high-frequency current passes through the tissue grasped between the electrodes, heating it and causing proteins in the blood to denature. The final result is a burst-resistant seal of partially denatured proteins, which can be transected with no or minimal bleeding.[54] A 3-L Tedlar bag (CEL Scientific Corp, Cerritos, CA) was connected to one of the trocars via a

Table 2. Summary of the 6 Operations During Which Surgical Smoke Samples Were Taken From the Pneumoperitoneum of the Patient.

	Operation				Patient			Measured With		
No.	Surgery	Anesthesia	OR Time (Minutes)	Blood Loss (mL)	Age (Years)	Gender	BMI	DFG	NIR	FTIR
1	Sigmoid resection for cancer	GA with sevoflurane	135	50	36	M	21.6	5	—	1
2	Sigmoid resection for diverticulitis	GA with sevoflurane	225	100	31	M	34.6	6	—	—
3	Sigmoid resection for diverticulitis	GA with sevoflurane	180	100	49	M	29.6	5	—	—
4	Rectosigmoid resection for cancer	GA with sevoflurane	220	20	76	F	26.6	9	—	—
5	Sigmoid resection for diverticulitis	GA with sevoflurane	145	100	85	M	24.1	1	3	—
6	Sigmoid resection for diverticulitis	GA with sevoflurane	270	50	37	M	35.1	1	3	—

Abbreviations: OR, operating room; BMI, body mass index (kg/m^2); DFG, difference frequency generation spectrometer; NIR, near-infrared spectrometer; FTIR, Fourier-transform infrared spectrometer; GA, general anesthesia; M, male; F, female.

sterile gas tube. Gas from the pneumoperitoneum was sampled whenever the vessel-sealing device was active by opening the valve on the trocar. The small overpressure of 12 mm Hg of the carbon dioxide pneumoperitoneum was sufficient to fill the sample bag without requiring a pump.

Twenty-seven of the 31 samples were measured with a difference frequency generation (DFG)–based infrared laser spectrometer, described in detail elsewhere.[55] Briefly, the DFG spectrometer can measure the absorption spectrum of a gaseous sample between 3.18 and 3.55 μm. In this range, many volatile organic compounds manifest strong and characteristic absorption features. Carbon dioxide, which was used as insufflant during the surgeries, does not absorb in this range and, therefore, does not interfere with the detection of other species. With a second laser spectrometer based on the wavelength modulation technique,[56,57] 6 of the 31 samples were measured with respect to carbon monoxide (CO) and hydrogen fluoride (HF) content. In these cases, the laser source was a distributed feedback laser diode emitting in the near infrared (NIR) at 2.33 μm for CO and at 2.43 μm for HF (both diodes were from nanoplus GmbH, Gerbrunn, Germany). The motivation for the measurement of HF is that we have observed the production of HF in lab experiments where an electrical discharge from a monopolar electroknife (Coagulasem, Dolley SA, Montrouge, France) took place in a sevoflurane vapor atmosphere. Neither CO nor HF absorbs between 3.18 and 3.55 μm, hence they cannot be detected with the DFG spectrometer. One sample was measured with a commercial Fourier-transform infrared (FTIR) spectrometer (model IFS 66v, Bruker Optics, Billerica, MA) between 2 and 11 μm. All 3 spectrometers used multiple pass gas cells in which the light beam is reflected back and forth between 2 mirrors to increase the total absorption pathlength, thereby increasing the sensitivity. For the DFG spectrometer, the total absorption pathlength was 34.5 m, for the NIR spectrometer it was 8 m, and for the FTIR spectrometer it was 4 m. The sensitivity of each spectrometer can be given as the minimum measurable concentration of one or more compounds, called the limit of detection (LOD). This value depends on the amount of noise present in the measured signal, on signal distortions due to optical interference fringes, on detector or light source drifts, on vibrations, and on changes in environmental conditions (eg, air temperature and pressure). Additionally, the presence of a strongly absorbing compound in the measured gas mixture may hinder the detection of an additional species with an overlapping absorption spectrum. For the NIR spectrometer, the LODs were 250 ppb (parts per billion) for CO and 110 ppt (parts per trillion) for HF; for the DFG and FTIR spectrometers LODs of selected compounds are given in a table later in the text. Although the number of volatile substances detectable with laser spectroscopy is smaller compared with other techniques (eg, gas chromatography/mass spectrometry), concentrations are more easily obtainable.

The chemical composition of the samples measured with the DFG and FTIR spectrometers was determined by fitting the measured absorption spectra with a collection of reference infrared spectra (Pacific Northwest National Laboratory[58]) with the help of a special algorithm.[59] By using all the known absorption lines in the available spectral range, the resulting concentration values are very robust against noise and interference from, for example, overlapping absorption lines belonging to other substances. The algorithm provides the constituents of the sample and their concentrations. With the NIR spectrometer, only CO and HF were monitored. This spectrometer was calibrated with a reference mixture of CO in nitrogen.

Results

The infrared absorption spectrum of a sample taken during surgery 2 (see Table 2) and measured between 3.18 and 3.45 μm with the DFG spectrometer is shown in

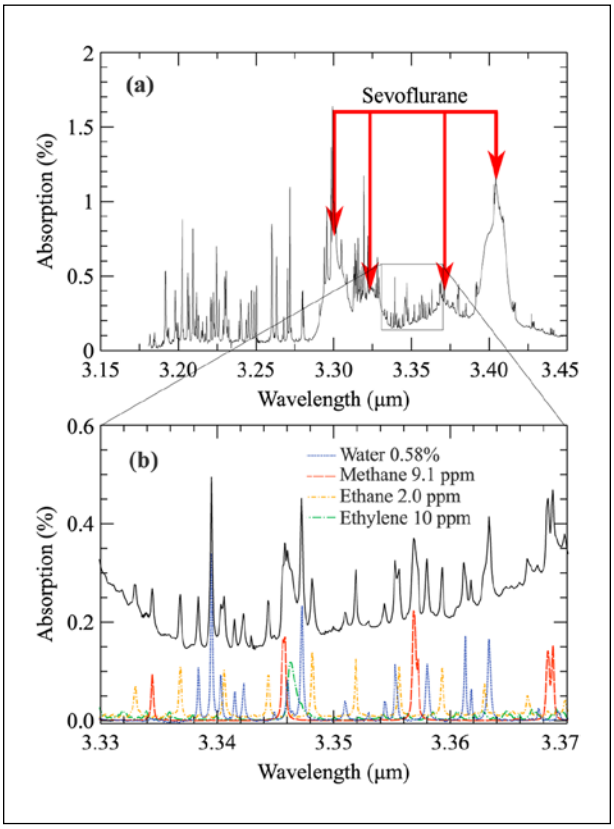

Figure 1. (A) Absorption spectrum of a sample of surgical smoke collected during surgery 2 and measured between 3.18 and 3.45 μm with the difference frequency generation spectrometer. The 4 absorption features indicated are because of sevoflurane vapour ($C_4H_3F_7O$). (B) Magnification of (A) between 3.33 and 3.37 μm. All the narrow absorption lines can be attributed to water vapor (H_2O), methane (CH_4), ethane (C_2H_6), and ethylene (C_2H_4) with the given concentrations. Total absorption pathlength = 34.5 m, pressure = 960 mbar, temperature = 30°C.

Figure 1. The 4 broad absorption features indicated in Figure 1A are due to sevoflurane vapor. Sevoflurane is not part of the spectral library used for the identification and quantification of the components of the gas mixture,[58] hence it could not be identified at first. Only after we measured the absorption spectrum of the vapors of Sevorane (Abbott AG, Baar, Switzerland; Sevorane is pure sevoflurane), a volatile anesthetic used in all procedures during which samples were taken, the identification became possible. The narrow absorption lines visible throughout the spectrum belong to water vapor, methane, ethane, and ethylene. As mentioned earlier, CO and HF cannot be detected in this wavelength range (3.18-3.45 μm). They were measured separately with the NIR spectrometer at 2.33 and 2.43 μm.

Few of the samples presented in this study were measured repeatedly (4-5 times) to verify the reproducibility of the obtained concentrations. The standard deviation of the concentration depends on the substance: ±5 ppm for sevoflurane, ±0.2 ppm for methane and ethane, ±1 ppm for ethylene, and ±0.03% for water vapor.

The measured concentrations of sevoflurane, methane, ethane, ethylene, water vapor, CO and HF are summarized in Table 3. The samples are sorted in the order they were collected. The first sample was always taken shortly after the vessel-sealing device had been employed for the first time during that operation. Samples were collected throughout the procedure until the vessel-sealing device had been used for the last time. For samples that were measured repeatedly, their average concentrations are given in Table 3.

Discussion

The concentrations of sevoflurane, methane, ethane, ethylene, and water vapor for all measured samples (Table 3) are shown in Figure 2. The box-and-whisker plots indicate the minimum, first quartile, median, mean, third quartile, and maximum concentration for each compound. The hatched areas denote concentrations below the LOD. There is no apparent correlation between the concentrations of sevoflurane, water vapor, methane, ethane, and ethylene. A correlation between methane, ethane, and ethylene is possible, but there are insufficient data points in the detectable range to provide a meaningful correlation coefficient. The chemical composition of the measured samples is summarized in Table 4 and a description of the health hazard linked to the exposure to these substances is presented in Table 5. Unsurprisingly, water vapor was detected in all samples with concentrations ranging from 0.27% to 1.1% (2700-11 000 ppm). Methane, ethane, and ethylene were detected in 19, 3, and 2 samples, respectively, out of the 27 measured. The recommended exposure limit (MAK) for all 3 compounds is 10 000 ppm.[30] The concentrations of the aforementioned substances vary from sample to sample, as can be seen in Table 3. However, they do not systematically increase during the course of the operation.

A few smoke samples were produced with the monopolar setting of the vessel-sealing device. Compared with smoke produced with the bipolar setting, no significant difference could be found. However, these samples were not measured with the NIR spectrometer, so no claim about the differences in CO (and HF) content can be made. HF could not be detected in any of the 6 measured samples (LOD = 110 ppt). In 4 of the 6 measured samples, CO was found with concentrations between 0.3 and 3.2 ppm. The MAK value for CO is 30 ppm.[30] All these concentrations are significantly smaller than reported in earlier studies (eg, 326 ppm,[27] >490 ppm[11]). However, a direct comparison cannot be made since the procedure and tools were different.

Table 3. Results of the Chemical Analysis of the 31 Collected Gas Samples.[a]

	Concentrations								Concentrations						
No.	H_2O (%)	Sevo (ppm)	CH_4 (ppm)	C_2H_6 (ppm)	C_2H_4 (ppm)	CO (ppm)	HF (ppb)	No.	H_2O (%)	Sevo (ppm)	CH_4 (ppm)	C_2H_6 (ppm)	C_2H_4 (ppm)	CO (ppm)	HF (ppb)
1b	1.10	450	0.76	<0.1	<5	—	—	4a	0.89	56	<0.1	<0.1	<5	—	—
1c	0.80	430	2.2	<0.1	<5	—	—	4b	0.61	59	<0.1	<0.1	<5	—	—
1d	0.27	180	0.40	<0.1	<5	—	—	4c	0.60	78	<0.1	<0.1	<5	—	—
1e	0.94	120	1.1	<0.1	<5	—	—	4d	0.44	110	0.15	<0.1	<5	—	—
1f	0.59	150	<0.1	<0.1	<5	—	—	4e	0.58	80	0.22	<0.1	<5	—	—
								4f	0.59	130	<0.1	<0.1	<5	—	—
2a	0.72	290	0.70	<0.1	<5	—	—	4g	0.45	110	<0.1	<0.1	<5	—	—
2b	0.53	180	0.45	<0.1	<5	—	—	4h	0.55	69	0.16	<0.1	<5	—	—
2c	0.65	160	0.39	<0.1	<5	—	—	4i	0.60	87	0.15	<0.1	<5	—	—
2d	0.68	120	2.2	0.19	<5	—	—								
2e	0.58	240	5.3	1.1	6.3	—	—	5a	—	—	—	—	—	0.30	<0.11
2f	0.58	300	9.1	2.0	10	—	—	5b	—	—	—	—	—	<0.25	<0.11
								5c	0.99	250	<0.1	<0.1	<5	<0.25	<0.11
3b	0.79	<20	1.1	<0.1	<5	—	—								
3c	0.68	<20	1.3	<0.1	<5	—	—								
3d	0.89	<20	<0.1	<0.1	<5	—	—	6a	0.47	<20	<0.1	<0.1	<5	3.2	<0.11
3e	0.83	<20	1.3	<0.1	<5	—	—	6b	—	—	—	—	—	2.6	<0.11
3f	0.78	<20	0.45	<0.1	<5	—	—	6c	—	—	—	—	—	1.4	<0.11

Abbreviations: H_2O, water vapor; Sevo, sevoflurane; CH_4, methane; C_2H_6, ethane; C_2H_4, ethylene; CO, carbon monoxide; HF, hydrogen fluoride.
[a]Samples 1b to 1f were collected from operation 1 (see Table 2), samples 2a to 2f from operation 2, and so on. Samples 1a and 3a were reference measurements and are not shown. A dash (—) indicates that the substance was not measured.

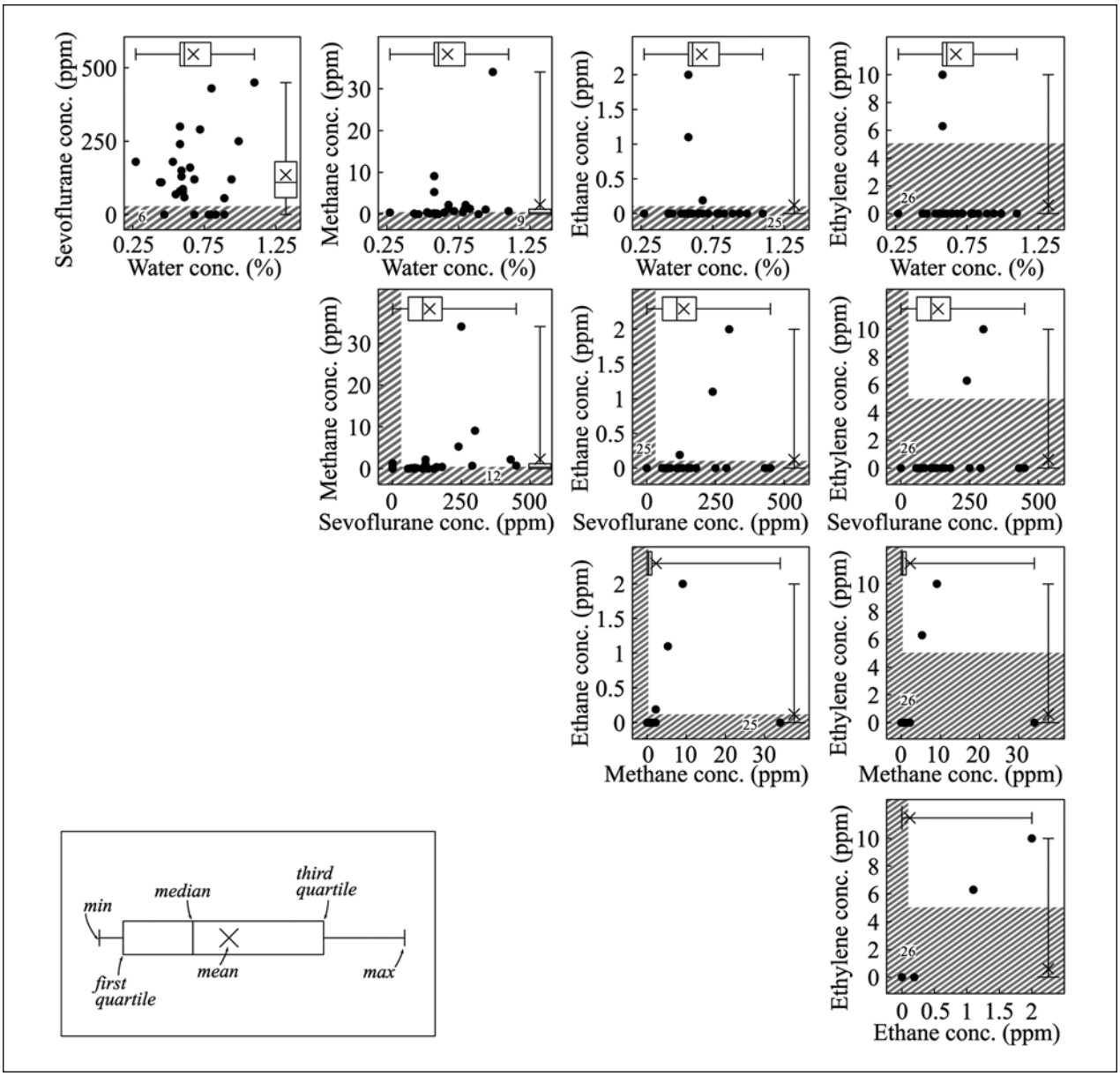

Figure 2. Measured concentrations of the 5 compounds—sevoflurane, methane, ethane, ethylene, and water vapor—pairwise grouped, in 28 measured samples of surgical smoke. The hatched areas indicate concentrations below the limits of detection (LOD, Table 4). The numbers within the hatched areas indicate in how many samples at least 1 of the 2 substances were not detected.

Relatively large concentrations of the volatile anesthetic sevoflurane were found in 21 of 27 measured samples, with concentrations of up to 450 ppm. This value is significantly higher than the threshold of 2 ppm recommended by NIOSH.[53] Our data suggest that gas released from the pneumoperitoneum—intentionally or because of leakage—might contribute to exposure of OR personnel to waste anesthetic gas. It should be noted, however, that the data given in Table 4 correspond to the concentrations in the pneumoperitoneum: When gas is released into the OR, a dilution occurs. Furthermore, ORs are often strongly ventilated (NIOSH recommends >15 air exchanges per hour[50]). Hence, concentrations in the OR could be orders of magnitude lower.

The measurement performed with the FTIR spectrometer, which provides access to a much broader spectral range (2-11 µm), confirmed the presence of sevoflurane, but no additional substances were discovered.

Apart from CO, none of the toxic compounds listed in Table 1 could be confirmed in this study. Some of them do

Table 4. Detected Chemical Compounds in the 31 Measured Samples of Surgical Smoke, With Limit of Detection (LOD), Recommended Exposure Limit (MAK[30]), and Whether the Measured Maximum Concentration Is Less Than the MAK Value or Not.

		Concentration (ppm)				
Substance	No. of Samples	Median	Range	LOD	MAK	Less Than MAK
Carbon monoxide (CO)	6	0.85	<0.25-3.20	0.25	30	Yes
Hydrogen fluoride (HF)	6	<0.00011	<0.00011	0.00011	1	Yes
Sevoflurane ($C_4H_3F_7O$)	**27**	**110**	**<20-450**	**20**	**2[a]**	**No**
Methane (CH_4)	27	0.39	<0.1-34.0	0.1	10 000	Yes
Ethane (C_2H_6)	27	<0.1	<0.1-2.0	0.1	10 000	Yes
Ethylene (C_2H_4)	27	<5	< 5–10	5	10 000	Yes
Water vapor[b] (H_2O)	27	0.61%	0.27% to 1.1%	—	—	Yes

[a]In Switzerland, there is no MAK value for sevoflurane. However, the US National Institute for Occupational Safety and Health recommends exposure limits of 2 ppm for all halogenated anesthetics.[53]
[b]Absolute water vapor concentration.

Table 5. Health Hazard Posed by the Detected and/or Detectable Substances (see Table 4).

Substance	Health Hazard	Recommended Exposure Limit (MAK)
Methane CH_4	Nontoxic. Can become dangerous at very high concentrations by reducing the oxygen concentration in the air (asphyxiant gas) and by forming an explosive gas mixture (flammability limits: 5% to 15%). Combustion produces carbon monoxide (CO) and dioxide (CO^2)	1%
Ethane C_2H_6	Nontoxic (asphyxiant gas), same hazard as for methane (flammability limits: 3% to 12.5%). Combustion produces CO and CO_2	1%
Ethylene C_2H_4	Nontoxic (asphyxiant gas), same hazard as for methane (flammability limits: 2.7% to 36%). Combustion produces CO and CO_2	1%
Carbon monoxide CO	Highly toxic (by inhalation), colorless, and odorless gas. Depending on the concentration and duration of exposure, may cause headache, dizziness, rapid breathing, pallor, cyanosis, nausea, excess salivation, vomiting, convulsions, unconsciousness, and death	30 ppm
Hydrogen fluoride HF	Highly toxic (by inhalation, ingestion, skin contact, and eye contact) colorless gas with irritating odor. Generates extremely corrosive hydrofluoric acid in contact with water or moisture. If inhaled, can cause lung inflammation (chemical pneumonitis), lung bleeding (pulmonary hemorrhage), and abnormal fluid buildup in the lungs (pulmonary edema). Can cause severe burns on contact with skin, which might not be immediately noticeable	1 ppm
Sevoflurane $C_4H_3F_7O$	Volatile anesthetic used in surgery at concentrations in the percentage range. Combustion products include CO, CO_2, HF, and COF_2 (fluorophosgene, a highly toxic gas). Long-term exposure on animals has been shown to affect fertility.[51] Effects of long-term exposure on humans are unknown	2 ppm[a]

[a]In Switzerland, there is no MAK value for sevoflurane. However, the US National Institute for Occupational Safety and Health recommends exposure limits of 2 ppm for all halogenated anesthetics.[53]

not absorb in the spectral range accessible with our spectrometer and, therefore, cannot be detected. Furthermore, it is likely that the smoke composition depends, both quantitatively and qualitatively, on whether the pyrolysis took place in an anoxic environment (such as in the carbon dioxide pneumoperitoneum in laparoscopic surgery) or in

Table 6. Limits of Detection (LOD) for the DFG Spectrometer and, in Parentheses, for the FTIR Spectrometer, and Recommended Exposure Limits (MAK[30]) for Some Toxic Chemical Species Detected in Surgical Smoke in Earlier Studies but Not in This Study.

Substance	LOD (ppm)	MAK (ppm)	LOD < MAK
Toluene	8.8	50	Yes
Styrene	11	20	Yes
Acetone	14	150	Yes
p-Xylene	6.5	100	Yes
m-Xylene	7.7	100	Yes
o-Xylene	7.6	100	Yes
Ammonia	750 (1)	20	Yes
Formaldehyde	*0.78 (2.5)*	*0.3*	*No*
Benzene	*8.7 (11)*	*0.5*	*No*
Acrylonitrile	*150 (4)*	*2*	*No*

an oxygen-rich atmosphere (such as in open and cosmetic surgery[12]). Substances found in smoke from open surgery should not necessarily be expected in smoke from laparoscopic surgery, and vice versa. Furthermore, the temperatures reached with vessel-sealing devices such as the one employed in the present study are considerably lower than those achieved with other electrocautery equipment or lasers. Previous studies often employed techniques that, despite only delivering qualitative results, were more sensitive than the ones used in this study. It is possible that many of the substances detected in other studies were present in our samples as well, but remained undetected because of their small concentrations. However, from a health hazard perspective, as long as the LOD is lower than the recommended exposure limit, the substance can be considered harmless if it is not detected.

In Table 6, the LOD and recommended exposure limits (MAK) are given for a selection of compounds. The upper part of Table 6 lists substances for which the LOD is below the MAK value (LOD < MAK): Since they were not detected, they can be considered harmless for OR personnel as their concentration is $c < \text{LOD} < \text{MAK}$. The lower part of Table 6, however, contains substances for which the LOD is larger than the MAK value (MAK < LOD): If present in surgical smoke, these might have concentrations lower than the LOD but larger than the MAK value ($\text{MAK} < c < \text{LOD}$). In this case a health hazard cannot be excluded, but the same discussion as above about the dilution following gas being released from the pneumoperitoneum into a sufficiently ventilated OR applies here as well.

As far as OR personnel are concerned, comparisons of measured concentrations with MAK values are a good starting point for the risk assessment of exposure to surgical smoke. However, the same does not apply to the patients undergoing surgery. Toxic compounds (eg, CO) present in the pneumoperitoneum can be absorbed into the blood circulation.[27] Available MAK values (or equivalent thresholds in other countries) do not apply to this kind of exposure.

Conclusions

In order to establish the health hazard linked to the exposure to surgical smoke, we have collected gas samples from the pneumoperitoneum of 6 patients undergoing laparoscopic surgery (Table 2) and analyzed them with respect to their chemical composition with 2 laser spectrometers and a FTIR spectrometer. Only water vapor, methane, ethane, ethylene, CO, and sevoflurane were detected (Table 4, Figure 2). Concentrations of methane, ethane, and ethylene were orders of magnitude below their recommended exposure limit.[30] Concentrations of CO were also below dangerous levels stipulated for OR personnel. The relatively large concentrations of sevoflurane vapors in the pneumoperitoneum could contribute to waste anesthetic gas pollution in the OR if gas is released or leaks from the abdominal cavity. Despite the large number of compounds reported to be present in surgical smoke in earlier studies (Table 1), surprisingly few could be confirmed here. The sensitivity of our spectrometers might not be sufficient to detect them, but for several frequently reported compounds (eg, toluene, styrene, xylene), the sensitivity is sufficient to exclude a health hazard for OR personnel, since limits of detection for those substances are below their MAK values (Table 6). However, special attention should be paid to benzene, a known carcinogen, which was reported in numerous previous studies[1,11,13-19] and which we could not measure with sufficient sensitivity here.

Authors' Note

Dieter Hahnloser is currently at Service de chirurgie viscérale, Centre Hospitalier Universitaire Vaudois (CHUV), BH10-206, Rue du Bugnon 46, 1011 Lausanne, Switzerland.

Michele Gianella is currently at Department of Chemistry, Physical and Theoretical Chemistry Laboratory, University of Oxford, South Parks Road, Oxford OX1 3QZ, United Kingdom.

Declaration of Conflicting Interests

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References

1. Barrett W, Garber S. Surgical smoke—a review of the literature: is this just a lot of hot air? *Surg Endosc*. 2007;17:979-987.

2. Alp E, Bijl D, Bleichrodt RP, Hansson B, Voss A. Surgical smoke and infection control. *J Hosp Infect*. 2006;62:1-5.
3. Garden JM, O'Banion MK, Bakus AD, Olson C. Viral disease transmitted by laser-generated plume (aerosol). *Arch Dermatol*. 2002;138:1303-1307.
4. Ferenczy A, Bergeron C, Richart R. Carbon dioxide laser energy disperses human papillomavirus DNA onto treatment fields. *Am J Obstet Gynecol*. 1992;163:1271-1274.
5. Jewett D, Heinsohn P, Bennett C, Rosen A, Neuilly C. Blood-containing aerosols generated by surgical techniques—a possible infectious hazard. *Am Ind Hyg Assoc J*. 1992;53:228-231.
6. Heinsohn P, Jewett D. Exposure to blood-containing aerosols in the operating room—a preliminary study. *Am Ind Hyg Assoc J*. 1993;54:446-453.
7. Tomita Y, Mihashi S, Nagata K, et al. Mutagenicity of smoke condensates induced by CO_2-laser irradiation and electrocauterization. *Mutat Res*. 1981;89:145-149.
8. Moot AR, Ledingham KM, Wilson PF, et al. Composition of volatile organic compounds in diathermy plume as detected by selected ion flow tube mass spectrometry. *ANZ J Surg*. 2007;77:20-23.
9. Krones C, Conze J, Hoelzl F, et al. Chemical composition of surgical smoke produced by electrocautery, harmonic scalpel and argon beaming—a short study. *Eur Surg Acta Chirurg Austr*. 2007;39:118-121.
10. Al Sahaf OS, Vega-Carrascal I, Cunningham FO, McGrath JP, Bloomfield FJ. Chemical composition of smoke produced by high-frequency electrosurgery. *Ir J Med Sci*. 2007;176:229-232.
11. Weston R, Stephenson RN, Kutarski PW, Parr NJ. Chemical composition of gases surgeons are exposed to during endoscopic urological resections. *Urology*. 2009;74:1152-1154.
12. Hollmann R, Hort C, Kammer E, Nägele M, Sigrist MW, Meuli-Simmen C. Smoke in the operating theatre: an unregarded source of danger. *Plast Reconstr Surg*. 2004;114:458-463.
13. Spleiss M, Weber LW. Medium- and low-volatile organic compounds generated by laser tissue interaction. *Proc SPIE*. 1996;2923:168-177.
14. Sagar PM, Meagher A, Sobczak S, Wolff BG. Chemical composition and potential hazards of electrocautery smoke. *Br J Surg*. 1996;83:1792.
15. Spleiss M, Weber L, Meier T, Treffler B. Identification and quantification of selected chemicals in laser pyrolysis products of mammalian tissues. *Proc SPIE*. 1995;2323:409-422.
16. Albrecht H, Hagemann R, Wäsche W, Wagner G, Mueller GJ. Volatile organic components in laser and electrosurgery plume. *Proc SPIE*. 1994;2077:310-317.
17. Weigmann HJ, Lademann J, Liebetruth J. Characterization of laser-tissue interaction by laser plume species. *Proc SPIE*. 1994;2077:264-269.
18. Weigmann HJ, Lademann J, Meffert H, Sterry W. Permanent gases and highly volatile organic compounds in laser plume. *Proc SPIE*. 1996;2923:164-167.
19. Weber LW, Spleiss M. Estimation of risks by chemicals produced during laser pyrolysis of tissues. *Proc SPIE*. 1995;2323:464-471.
20. Francke W, Fleck O, Mihalache DL, Wöllmer W. Identification of volatile compounds released from biological tissue during CO_2 laser treatment. *Proc SPIE*. 1995;2323:423-431.
21. Hensman C, Baty D, Willis R, Cuschieri A. Chemical composition of smoke produced by high-frequency electrosurgery in a closed gaseous environment—an in vitro study. *Surg Endosc*. 1998;12:1017-1019.
22. Desinger K, Wäsche W, Albrecht H. Comparative investigation of pyrolysis products due to laser and RF surgery with regard to the latest device development. *Proc SPIE*. 1996;2624:234-239.
23. Wäsche W, Albrecht H, Mueller GJ. Determination of temperature dependence of the production of volatile organic compounds (VOCs) during the vaporization of tissue using Nd:YAG laser, CO_2 laser, and electrosurgery devices. *Proc SPIE*. 1995;2323:393-399.
24. Albrecht H, Wäsche W, Mueller GJ. Assessment of the risk potential of pyrolysis products in plume produced during laser treatment under OR conditions. *Proc SPIE*. 1995;2323:455-463.
25. Wäsche W, Albrecht H. Investigation of the distribution of aerosols and VOC in plume produced during laser treatment under OR conditions. *Proc SPIE*. 1996;2624:270-275.
26. Chung YJ, Lee SK, Han SH, et al. Harmful gases including carcinogens produced during transurethral resection of the prostate and vaporization. *Int J Urol*. 2010;17:944-949.
27. Esper E, Russell TE, Coy B, Duke BE, Max MH, Coil JA. Transperitoneal absorption of thermocautery-induced carbon-monoxide formation during laparoscopic cholecystectomy. *Surg Endosc*. 1994;4:333-335.
28. Wu J, Luttmann D, Meininger T, Soper N. Production and systemic absorption of toxic byproducts of tissue combustion during laparoscopic surgery. *Surg Endosc*. 1997;11:1075-1079.
29. US National Institute for Occupational Safety and Health. *Pocket Guide to Chemical Hazards* (Publication No. 2005-149). Washington, DC: Department of Health and Human Services; 2007.
30. SUVA. *Grenzwerte am Arbeitsplatz*. Lucerne, Switzerland: SUVA; 2009.
31. Accorsi A, Barbieri A, Raffi GB, Violante FS. Biomonitoring of exposure to nitrous oxide, sevoflurane, isoflurane and halothane by automated GC/MS headspace urinalysis. *Int Arch Occup Environ Health*. 2001;74:541-548.
32. Accorsi A, Valenti S, Barbieri A, Raffi GB, Violante FS. Proposal for single and mixture biological exposure limits for sevoflurane and nitrous oxide at low occupational exposure levels. *Int Arch Occup Environ Health*. 2003;76:129-136.
33. Byhahn C, Heller K, Lischke V, Westphal K. Surgeon's occupational exposure to nitrous oxide and sevoflurane during pediatric surgery. *World J Surg*. 2001;25:1109-1112.
34. Byhahn C, Wilke HJ, Westpphal K. Occupational exposure to volatile anaesthetics: epidemiology and approaches to reducing the problem. *CNS Drugs*. 2001;15:197-215.
35. Gentili A, Accorsi A, Pigna A, et al. Exposure of personnel to sevoflurane during paediatric anaesthesia: influence of professional role and anaesthetic procedure. *Eur J Anaesthesiol*. 2004;21:638-645.

36. Gustorff B, Lorenzl N, Aram L, Krenn CG, Jobst BP, Hoerauf KH. Environmental monitoring of sevoflurane and nitrous oxide using the cuffed oropharyngeal airway. *Anesth Analg*. 2002;94:1244-1248.
37. Hall JE, Henderson KA, Oldham TA, Pugh S, Harmer M. Environmental monitoring during gaseous induction with sevoflurane. *Br J Anaesth*. 1997;79:342-345.
38. Heijbel H, Bjurstöm R, Jakobsson JG. Personnel breathing zone sevoflurane concentration adherence to occupational exposure limits in conjunction with filling of vaporisers. *Acta Anaesthesiol Scand*. 2010;54:1117-1120.
39. Hobbhahn J, Hoerauf K, Wiesner G, Schrögendorfer K, Taeger K. Waste gas exposure during desflurane and isoflurane anaesthesia. *Acta Anaesthesiol Scand*. 1998;42:864-867.
40. Hobbhahn J, Wiesner G, Taeger K. Occupational exposure and environmental pollution: the role of inhalation anesthetics with special consideration of sevoflurane. *Anaesthesist*. 1998;47(suppl 1):77-86.
41. Hoerauf K, Funk W, Harth M, Hobbhahn J. Occupational exposure to sevoflurane, halothane and nitrous oxide during paediatric anaesthesia—waste gas exposure during paediatric anaesthesia, *Anaesthesia*. 1997;52:215-219.
42. Hoerauf KH, Koller C, Taeger K, Hobbhahn J. Occupational exposure to sevoflurane and nitrous oxide in operating room personnel. *Int Arch Occup Environ Health*. 1997;69:134-138.
43. Hoerauf K, Hartmann T, Zavrski A, et al. Occupational exposure to sevoflurane during sedation of adult patients. *Int Arch Occup Environ Health*. 1999;72:174-177.
44. Hoerauf KH, Wallner T, Akça O, Taslimi R, Sessler DI. Exposure to sevoflurane and nitrous oxide during four different methods of anesthetic induction. *Anesth Analg*. 1999;88:925-929.
45. Hoerauf KH, Hartmann T, Acimovic S, et al. Waste gas exposure to sevoflurane and nitrous oxide during anaesthesia using the oesophageal-tracheal Combitube small adult. *Br J Anaesth*. 2001;86:124-126.
46. Raj N, Henderson KA, Hall JE, et al. Evaluation of personal, environmental and biological exposure of paediatric anaesthetists to nitrous oxide and sevoflurane. *Anaesthesia*. 2003;58:630-636.
47. Rasmussen H, Thorud S. Using a refrigerant leak detector to monitor waste gases from halogenated anesthetics. *J Am Assoc Lab Anim Sci*. 2007;46:64-68.
48. Summer G, Lirk P, Hoerauf K, et al. Sevoflurane in exhaled air of operating room personnel. *Anesth Analg*. 2003;97:1070-1073.
49. Tankó B, Molnár C, Budi T, Peto C, Novák L, Fülesdi B. The relative exposure of the operating room staff to sevoflurane during intracerebral surgery. *Anesth Analg*. 2009;109:1187-1192.
50. US National Institute for Occupational Safety and Health. *Waste Anesthetic Gases: Occupational Hazards in Hospitals* (Publication No. 2007-151). Washington, DC: Department of Health and Human Services; 2007.
51. Ceyhan A, Cincik M, Bedir S, Ustun H, Dagli G, Kalender H. Effects of exposure to new inhalational anesthetics on spermatogenesis and sperm morphology in rabbits. *Arch Androl*. 2005;51:305-315.
52. Ozer M, Baris S, Karakaya D, Kocamanoglu S, Tur A. Behavioural effects of chronic exposure to subanesthetic concentrations of halothane, sevoflurane and desflurane in rats. *Can J Anaesth*. 2006;53:653-658.
53. US National Institute for Occupational Safety and Health. *Criteria for a Recommended Standard: Occupational Exposure to Waste Anesthetic Gases and Vapors* (Publication No. 77-140). Washington, DC: Department of Health and Human Services; 1977.
54. Kennedy J, Stranahan P, Taylor K, Chandler J. High-burst-strength, feedback-controlled bipolar vessel sealing. *Surg Endosc*. 1998;12:876-878.
55. Gianella M, Sigrist MW. Automated broad tuning of difference frequency sources for spectroscopic studies. *Appl Opt*. 2011;50:A11-A19.
56. Bomse DS, Stanton AC, Silver JA. Frequency modulation and wavelength modulation spectroscopies—comparison of experimental methods using a lead-salt diode-laser. *Appl Opt*. 1992;31:718-731.
57. Silver J. Frequency-modulation spectroscopy for trace species detection—theory and comparison among experimental methods. *Appl Opt*. 1992;31:707-717.
58. Sharpe SW, Johnson TJ, Sams RL, Chu PM, Rhoderick GC, Johnson PA. Gas-phase databases for quantitative infrared spectroscopy. *Appl Spectrosc*. 2004;58:1452-1461.
59. Gianella M, Sigrist MW. Improved algorithm for quantitative analyses of infrared spectra of multicomponent gas mixtures with unknown compositions. *Appl Spectrosc*. 2009;63:338-343.