Quantitative *in vitro* analysis of surgical smoke by laser photocoustic spectroscopy

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CO_2 laser photoacoustic spectroscopy is used to detect and monitor gases at low concentrations, in the range of ppb (part per billion) or even lower. In the present paper, chemical compounds of surgical smoke produced *in vitro* by CO_2 laser ablation of fresh animal tissues, in nitrogen or synthetic air atmospheres, were investigated by CO_2 laser photoacoustic spectroscopy. A quantitative analysis of some gases from surgical smoke was achieved. Traces in ppm (part per million) range of benzene, ethylene, ammonia, and methanol were detected in the samples which consisted mostly of carbon dioxide and water vapors. The relationships between gas concentrations and laser power, exposure time, atmosphere and the type of tissue were investigated. The CO_2 laser photoacoustic spectroscopy system proved once again its efficiency in gas concentration measurement with high sensitivity, over a large span of concentration values.

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1. Introduction

The use of thermal instruments for surgical applications has grown significantly over the past three decades. Unfortunately, when any type of thermal or ultrasonic surgical instrument, such as laser energy, electrosurgery, argon, ultrasonic/harmonic scalpel, or plasma is applied to human tissue, an unwanted by-product is produced which is commonly known as surgical smoke plume [1-5]. Surgical smoke has been shown to be a viable transport mechanism for viruses [1–5], blood and cell containing aerosols [5–7] and tissue fragments [8, 9]. There are several ways by which surgical smoke affects patients and health care professionals present in the operating room, depending on the size, nature and concentration. For example, laser produced smoke is characterized by small particles with a diameter of approximately 0.3 μm [10] that generally pose a chemical hazard. Therefore, from the health safety perspective, the chemical and biological composition of surgical smoke is of great interest.

The toxicity and mutagenicity of surgical smoke has been said to be at least as severe as that of cigarette smoke [6-9]. In fact, the smoke issued from laser ablation of 1 gram of tissue can be compared to the burden derived from 3 cigarettes; for electrocautery, the number is 6 cigarettes [9].

In this work, we present the results of quantitative analysis of trace gas concentrations (ethylene, benzene, ammonia, and methanol) and water vapors content from surgical smoke produced *in vitro* in our laboratory on fresh animal tissue, in nitrogen or synthetic air atmosphere, analyzed with CO_2 laser photoacoustic spectroscopy. We also investigated the relationship between smoke composition and laser irradiation power, exposure time, atmosphere and type of the tissue.

The CO_2 laser photoacoustic spectroscopy technique has the advantage of high selectivity, necessary to distinguish the gas species present in a multicomponent gas mixture, such as surgical smoke, together with a high sensitivity to detect very low concentrations of gases. Detection limits in the bands of ppb and ppt, good selectivity, and a relative experimental simplicity are some aspects that make photoacoustic spectroscopy a great tool for the detection of trace gases [11-14]. Moreover, the CO_2 laser photoacoustic spectroscopy technique holds a great potential for medical diagnostics and monitoring of human breath biomarkers [15].

The smoke was produced by CO_2 laser irradiation; one of the most frequently used lasers in medicine. The interaction of the laser beam with the tissue is purely thermal and, as a consequence, the production of smoke is rather high. From the multitude of volatile compounds present in the CO_2 laser surgery smoke, the four gases under observation were chose based on their high absorption coefficient in the CO_2 laser wavelength range, as well as due to their influence on the immediate and long-term health of those who inhale them.

Benzene is a mutagen which can lead to headaches, as well as irritation and soreness in the eyes, nose and throat. Benzene targets liver, kidney, lung, heart and the brain causing cancer or increasing the risk of cancer, DNA strand breaks, and chromosomal damage [16-19]. Ethylene is considered a human carcinogen and can be metabolized to ethylene oxide, which is a respiratory irritant and cause pulmonary edema, much more than other irritant gases do. Ethylene have been shown to present a mutagenic and carcinogenic potential similar to that of the cigarette smoke [20,21]. The lowest concentration of ammonia in air is irritating eyes, nose and throat [22]. Ammonia tends to block oxygen transfer from the gills to the blood and can cause both immediate and long term gill damage, while methanol is a toxic alcohol that produces a typical intoxication similar to ethanol [23]. Within several hours, methanol is metabolized by the enzyme alcoholic dehydrogenase (ADH) to its toxic metabolites formaldehyde and formic acid which are human carcinogens [24].

2. Material and methods

2.1 CO_2 laser photoacoustic spectroscopy set-up

The trace gas concentrations from surgical smoke were measured *in vitro* employing the CO_2 laser photoacoustic spectroscopy system, used for the detection and measurement of trace gases at very low concentrations ppb or even ppt (parts per trillion) [11], developed at National Institute for Laser, Plasma and Radiation Physics, Bucharest, Romania. The photoacoustic system is illustrated in Fig. 1. The experimental set-up consists of a line-tunable CO_2 laser emitting radiation in the range of 9.2 – 10.8 µm, with a maximum output power of 5.5 W, a photoacoustic (PA) cell and a gas handling system [11,12].

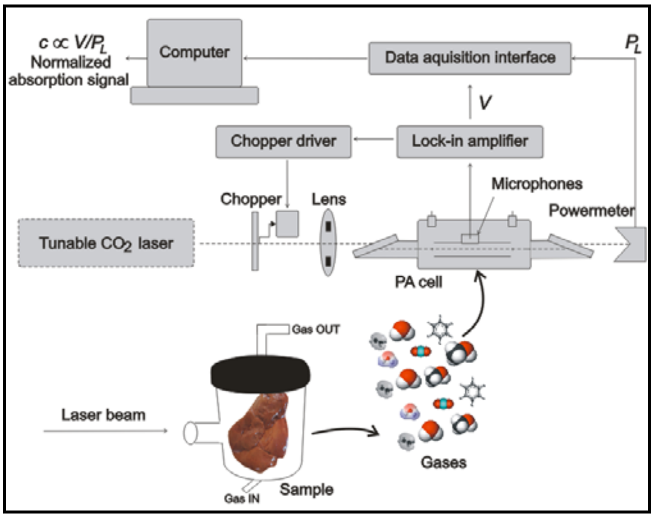

Fig. 1 The CO_2 laser phototacoustic spectroscopy system.

The requirement for the gases to be detected is that they should possess high absorption strength in the wavelength range of the CO_2 laser (9.2 – 10.8 µm), so we choose for each gas the corresponding laser line with the highest absorption coefficient (see Table 1). As methodology, the CO_2 laser is sequentially tuned to the peak of a strong absorption line of the species to be monitored, and then the PA signal is measured.

Table 1. Type of gases measured from surgical smoke with the corresponding laser line, wave number and the absorption coefficient.

Type of gas	Laser line	Power on laser line [W]	Wavelength [µm]	Wave number [cm^{-1}]	Absorption coefficient [$cm^{-1}atm^{-1}$]
Ethylene C_2H_4	10P(14)	4	10.53	949.75	30.4
Benzene C_6H_6	9P(30)	2.2	9.63	1037.77	2
Ammonia NH_3	9R(30)	1.5	9.22	1084.95	56
Methanol CH_3H	9P(34)	1	9.67	1033.81	21.8
Water vapor H_2O	10R(20)	4.5	10.24	976.27	$8.3x10^{-4}$

The trace gas concentration at each laser line was obtained from Eq. (1) by using the measured PA signal and the laser power, and knowing precisely the responsivity of the PA cell:

$$V = \alpha C S_M P_L c \quad (1)$$

where: V (V) is the photoacoustic signal; α ($cm^{-1}atm^{-1}$), the gas aborption coefficient at a given wavelength; C (Pa cm W^{-1}), the cell constant; S_M (V Pa^{-1}), the microphone responsivity; P_L (W), the cw laser power (unchopped value; 2x measured average value); and c (atm), the trace gas concentration (usually given in units of per cent, ppb, ppm or ppt).

As the surgical smoke is a mixture of gases, we should consider few theoretical and practical aspects. The PA spectrum of an arbitrary gas mixture is represented by a linear combination of the absorption spectra of all constituents. Hence, the absorption spectra of all expected constituents that contribute to the total absorption have to be determined prior to the analysis of a multicomponent gas mixture [11]. For example, in a nitrogen atmosphere including a mixture of n absorbing gases at unknown concentration levels c_1, c_2,..., c_n, low enough to assure linearity, the PA signal $V(\lambda)$ of the n absorbing compounds j (j = 1, 2, ... , n), with their concentration c_j and their wavelength-dependent absorption coefficients $\alpha_j(\lambda)$, is the sum of the individual signals from each compound [13]:

$$V(\lambda) = \sum_{j=1}^{n} V_j(\lambda) = R P_L(\lambda) \sum_{j=1}^{n} c_j \alpha_j(\lambda) \quad (2)$$

where, R (V cm/W) is the cell responsivity (voltage) of the PA cell or the calibration constant.

$$R = C S_M \quad (3)$$

Interference of other absorbing substances may impair the theoretical detection limit in a multicomponent analysis of the real samples. The CO_2 laser spectral outputs occur in the wavelength region where a large number of compounds possess strong absorption features and where absorptive interferences from water vapors, carbon dioxide, and other gaseous components may influence the measurements. Due to the additive character of the photoacoustic signal under normal pressure conditions, the presence of a large amount of water vapor and carbon dioxide in our smoke samples impedes the low concentration range detection (ppb). There are several ways to overcome this problem. One way is to partially remove CO_2 from the sample by absorbing it on a potassium hydroxide scrubber (KOH trap) inserted between the sampling cell and the PA cell. Taking into account the nature of specific chemical reactions involved in the CO_2 removal by KOH, a certain amount of water is also absorbed from the sample passing the scrubber. In this way, concentrations below 1 ppmV CO_2 can be achieved without influencing the concentration of the other gases [14].

2.2 Smoke production and sampling

Surgical smoke was produced by laser irradiation *in vitro* of fresh animal tissues. The animal tissue samples were purchased from a local packing company, according with the EU standard. The irradiation occurs using a CO_2 laser (GEM SELECT 50^{TM}), at different powers of the laser and for different duration of the exposure, e.g. 6, 10, and 15 W and exposure times of 3, 6, 12 and 20 seconds. For this purpose, we designed and built a simple cell (see Fig. 1) that allows the ablation of small volumes of tissue with the CO_2 laser in a selected atmosphere (nitrogen or synthetic air). The cell consists of a glass cylinder, fitted with a rubber stopper, connected to the gas handling system by a gas inlet and an outlet, and a glass tube at the end of which a ZnSe window was attached that allows the laser beam to enter the cell and produce the surgical smoke. The two gas connections permit to flush the buffering gas (nitrogen or synthetic air) which transports the smoke samples through the cell, the KOH scrubber trap, a low efficiency particle filter (retaining large particles with a diameter > 10 μm), to the final detection place, the PA cell. The PA cell is filled until the local atmospheric pressure (1024-1034 mbar) is reached. In what concerns the temperature, the tissue samples were kept prior to the experiment in the refrigerator, but sufficient time was allowed them to reach the ambient temperature before irradiation (27^{o}C). We can safely presume that the smoke reached the ambient temperature inside the cell. The large volume of the PA cell (1.2 l), together with the flow rate of the buffering gas gave us the certitude that all the smoke created in the glass cylinder was flushed into the detection cell.

To have accurate measurements of gas concentrations detection in smoke samples, new vacuum was realized in the photoacoustic system after each set of experiments. Furthermore to clean the PA cell we have pumped and flushed nitrogen or synthetic air. After that, for each laser line signals in nitrogen or synthetic air enclosed in the PA cell, were determined.

PA cell responsivity is an important parameter, which depends on the pressure of the gas inside the PA cell. The PA cell in smoke analysis was filled at atmospheric pressure, it is necessary to know the pressure dependence of the PA cell responsivity. The responsivity of the PA cell was determined by using a calibrated gas of ethylene, ammonia, benzene or methanol. The pressure dependence of the responsivity was measured always at the center of the CO2 laser line by using a frequency stabilized laser (instability $3x10^{-8}$).

Once the atmospheric pressure was attained in the PA cell, the detection process started, analyzing the surgical smoke with the CO_2 photoacoustic system described in the previous section.

3. Results and discussion

Table 2 summarizes some results obtained for different smoke samples and the irradiation conditions (laser power and irradiation time). The measurements were made at room temperature and atmospheric pressure, using fresh tissue samples each time. Benzene, ethylene, ammonia and methanol are the substances chosen to be monitored with our photoacoustic system. Each sample is a gas mixture dominated by water vapor and carbon dioxide, but after passing the KOH scrubber, the residual water vapors content is decreased to an average of 2.5%. The concentrations of the components benzene (C_6H_6), ethylene (C_2H_4), ammonia (NH_3), methanol (CH_3OH), and water vapors (H_2O) vary from sample to sample, depending on the irradiation parameters and the atmosphere (nitrogen or synthetic air).

Table 2: Summary of smoke samples. Parameters under observation: type of animal tissue, laser ablation power, exposure time of laser beam onto the tissue sample, concentration of gases and water vapor percentage.

Type of tissue	Power [W]	Exposure time [sec]	Atmosphere	C_2H_4 [ppm]	NH_3 [ppm]	C_6H_6 [ppm]	CH_3OH [ppm]	H_2O [%]
Pig spleen	6	12	Synthetic air	0.620	16	140	26.6	3.3
Pig spleen	6	20	Synthetic air	2.900	126	433	31.7	4.6
Pig spleen	6	12	Nitrogen	0.550	7.62	155	43	1.9
Pig spleen	6	20	Nitrogen	0.790	29	715	57	2.3
Pig lung	10	3	Nitrogen	0.696	9.14	334	43	3.7
Pig lung	10	6	Nitrogen	0.833	49	980	17	3.8
Pig kidney	15	3	Nitrogen	0.932	32	803	64	3.7
Pig kidney	15	3	Nitrogen	0.452	34	730	61	1.8
Pig skin	15	3	Nitrogen	1.360	39	830	61	3.7
Pig skin	15	3	Nitrogen	0.303	38	920	53	2.1
Pig liver	15	3	Nitrogen	0.947	32	803	64	1.9
Chicken liver	15	3	Nitrogen	0.670	10	980	57	1.5

At a first glance we have to look over the values we found in connection with the recommended and permissible exposure limits. Permissible exposure limits (PEL or OSHA-PEL) are established by the Occupational Safety and Health Administration (OSHA) and are the legal limits in the United States for exposure of an employee to a chemical substance or physical agent, usually given as a time-weighted average (TWA) over an 8-hour period, or short-term exposure limits (STEL) over 15 minutes. The recommended exposure limit (REL) is an occupational exposure limit that has been recommended by the United States National Institute for Occupational Safety and Health (NIOSH) to OSHA for adoption as a permissible exposure limit. The REL is a level that NIOSH believes would be protective of worker safety and health over a working lifetime if used in combination with controls, monitoring, and personal protective equipment. Although not legally enforceable limits, NIOSH RELs are considered by OSHA during the promulgation of legally enforceable PELs.

Table 3 shows the REL and PEL for each gas and the concentration range covered by our measurements. As can be seen, benzene was detected in high concentrations in all smoke samples, even hundreds of time higher than the exposure limit. Ammonia was also detected in the same smoke samples in concentrations that exceed the exposure limit. Ethylene and methanol are found at concentrations below the exposure limit. But, ethylene can be metabolized to ethylene oxide, which is a respiratory irritant and cause pulmonary edema, more than the other irritant gases do. The methanol is oxidized in the human liver and the metabolic products [12] including formaldehyde and formic acid are formed which are the real responsible for the toxic effects of methanol. The last three mentioned metabolic products are known to have carcinogenic and mutagenic effects.

Table 3. Comparison between the exposure limit and photoacoustic results of gas concentration

Gas	Permissible exposure limit		Recommended exposure limit (ppm)	Measured results (ppm)
	TWA (ppm)	STEL (ppm)		
Ethylene (C_2H_4)	-	-	200 [25]	0.303 ÷2.9
Ammonia (NH_3)	50	35	25 [22,23]	3.49 ÷ 126
Benzene (C_6H_6)	1-10	5-25	0,1 [16,17]	140 ÷ 980
Methanol (CH_3OH)	200	-	200 [24]	17 ÷ 64

However, the values measured in our experiments are given only for "*in vitro*" conditions, meaning that no correction was applied for the dependence with the distance to the emission source or for the influence of dilution in air due to air conditioning systems present in a surgery room, especially that most of the plume components are usually significantly reduced by evacuation systems placed in the proximity of the operatory field.

Regarding the correlation between gas concentrations and other parameters, Fig. 2 shows the influence of the atmosphere on the gas concentrations for smoke samples produced using the same irradiation parameters: 6 W laser power, 3 seconds irradiation time, for the same type of tissue (pig spleen). From Fig. 2 it can be observed that in nitrogen atmosphere, ethylene and ammonia are in higher concentrations than in synthetic air, while methanol and benzene behave vice-versa. The inverse behavior of methanol and benzene in synthetic air is due to its chemical reaction with the oxygen (20% present in synthetic air). Methanol and benzene reacts with the oxygen forming carbon dioxide and water.

Figure 3 shows the influence of the tissue type on gas concentrations. Surgical smoke was produced by irradiation of different types of animal tissue (chicken liver, pig liver, pig kidney, and pig skin) at a laser power of 6 W for 3 seconds in nitrogen atmosphere. In all four animal tissue samples it can be observed that gas concentrations do not vary in a large range, but benzene has a higher concentration, ammonia and methanol are in ppm range, while ethylene has a concentration of hundreds of ppb.

The influence of laser ablation power on the gas concentrations can be seen in Fig. 4. Analyzing the smoke produced by tissue ablation at 10 and 15 W laser power, in nitrogen atmosphere, irradiation time of 3 seconds, it can be observed that all four gas concentrations are increasing, but the ratio between them remains almost constant.

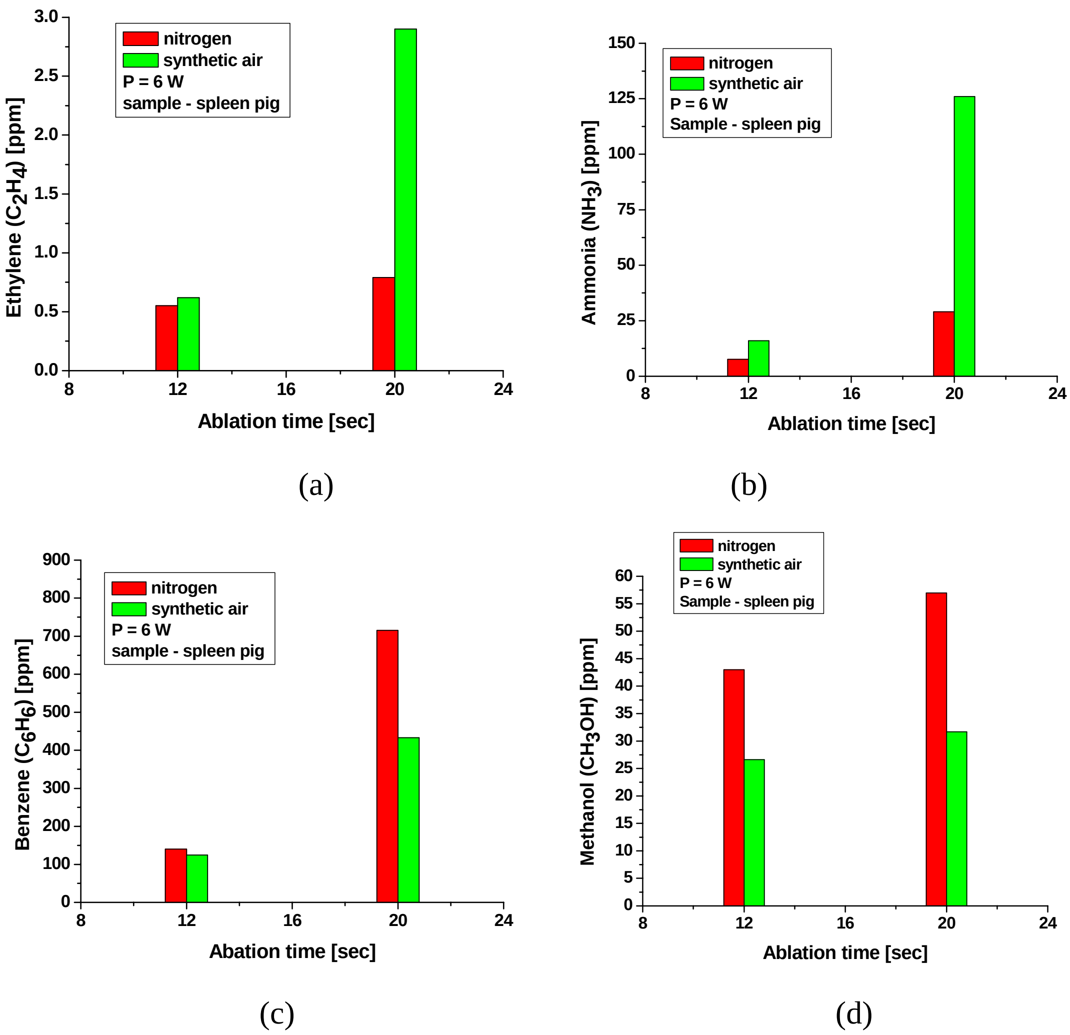

Fig. 2 Gas concentrations variation function of atmosphere (nitrogen or synthetic air), on pig spleen irradiated at P = 6 W and exposure time of 12 s and 20 s: (a) ethylene (C_2H_4); (b) ammonia (NH_3); (c) benzene (C_6H_6); (d) methanol (CH_3OH)

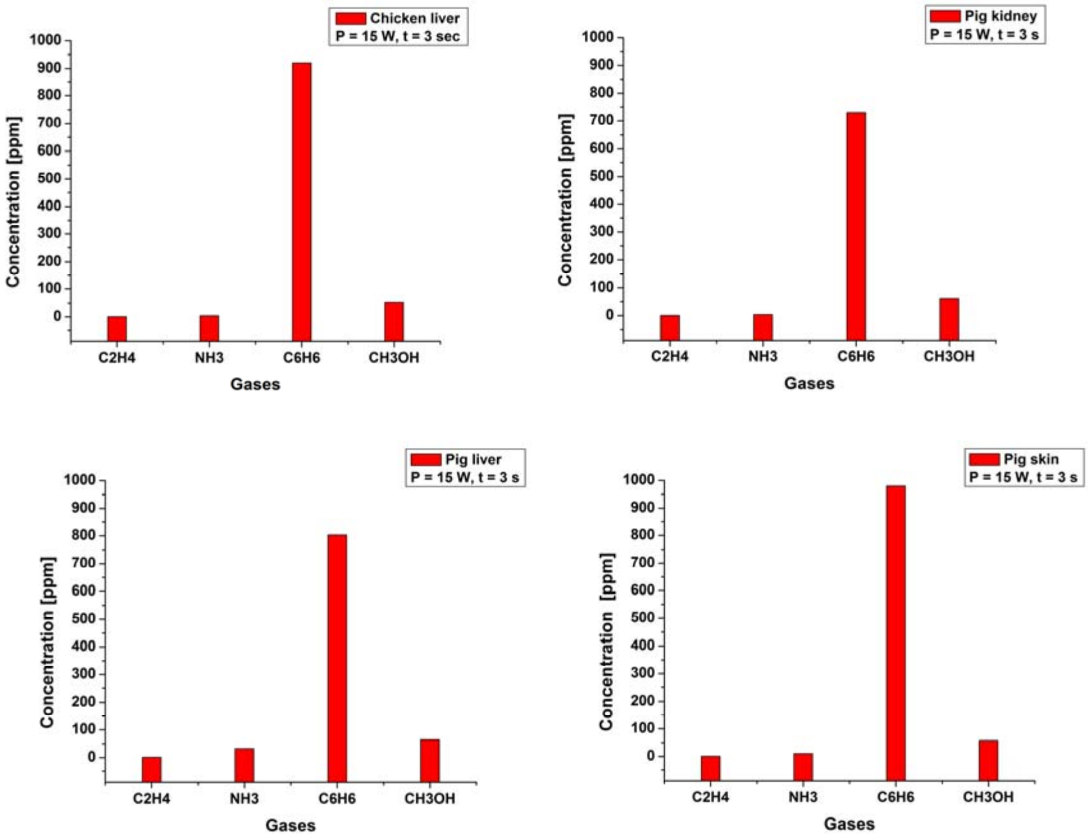

Fig. 3 Variation of gas concentrations for different tissue samples (chicken liver, pig kidney, pig liver, and pig skin) irradiated at P = 15 W for 3 s, in nitrogen atmosphere

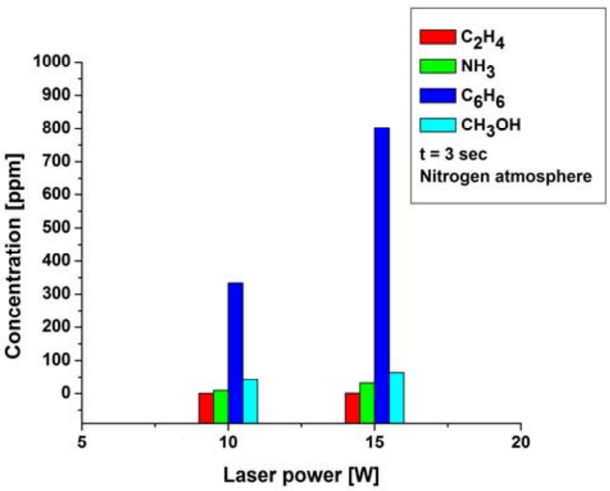

Fig. 4 Gas concentrations at laser ablation power of 10 W and 15 W and irradiation time of 3 s, in nitrogen atmosphere

4. Conclusions

In the present study, a quantitative analysis of surgical smoke produced *in vitro* by irradiation of animal tissues was made, using a CO_2 laser photoacoustic spectroscopy system. Benzene, ethylene, ammonia, methanol and water vapors are the compounds that were monitored in each measurement. Concentrations were in the ppm range for methanol, benzene and ammonia, in ppb range for ethylene, and percent range for water vapors.

We proved the presence of these four toxic gases in the surgical smoke produced by laser tissue ablation at quite high levels compared with the recommended exposure limits. Some of the concentrations are lower than the recommended values, but it has to consider the cumulative effect of all volatile compounds released during laser surgery, to which the influence of particles below 10 μm is added. Also, it should be stressed that through continuous exposure, the inhalation of surgical smoke becomes more harmful to the surgical team members.

Some relationships between gas concentrations and laser ablation power, exposure time, atmosphere and type of tissue were investigated. There was a clear influence of the atmosphere on the gas concentrations. Ethylene and ammonia are in higher concentrations in nitrogen than in synthetic air, excepting methanol and benzene concentrations that decrease in synthetic air. Decreased concentration of methanol and benzene in synthetic air is due to chemical reaction with the oxygen, from which carbon dioxide and water result.

The gas concentrations in smoke samples produced under the same conditions depends proportionally only with the laser ablation power and with the exposure time. The ratio between gas concentrations presents no significant variation function of the used tissue sample.

The CO_2 laser photoacoustic spectroscopy system proved its efficiency in absolute gas measurements with high sensitivity, over a large span of concentration values.

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