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SPECTROSCOPIC ANALYSIS OF SURGICAL SMOKE PRODUCED *IN VITRO* BY LASER VAPORIZATION OF ANIMAL TISSUES IN A CLOSED GASEOUS ENVIRONMENT

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Abstract. The surgical smoke is composed by gases, vapors, aerosols, biological fragments and particulate matter. A quantitative analysis of surgical smoke produced *in vitro* by CO_2 laser vaporization of different fresh animal tissues in closed nitrogen atmosphere was investigated. Using the laser photoacoustic spectroscopy technique, the concentration of acetonitrile, acrolein, ammonia, benzene, ethylene and toluene from surgical smoke was determined. Average concentrations of acetonitrile (190 ppm), acrolein (35 ppm), ammonia (25 ppm), benzene (20 ppm), ethylene (0.41 ppm), and toluene (45 ppm) were measured in the smoke samples. The correlation between gas concentration and laser power, exposure time or the tissue type was investigated.

Key words: CO_2 laser, laser photoacoustic spectroscopy, surgical smoke composition
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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 energy-based surgical instrument such as laser, high-frequency electric knives, and ultrasonic/harmonic scalpel is applied to human tissue, an unwanted by-product is produced, commonly known as surgical smoke. Surgical smoke is created when the laser energy is delivered to a tissue, owing to the heating of the tissue components. The heat vaporizes the intracellular fluid, which increases the pressure inside the cell and causes the cell membrane to burst. When this happens, a plume of smoke containing mostly water vapor is released into the atmosphere of the operating room. At the same time, the intense heat creates chars in the protein and other organic matter within the cell, and causes thermal necrosis in adjacent cells. The charring of cells releases other harmful contaminants, such as carbonized cell fragments and gaseous hydrocarbons in the form of aerosols, vapors and gases [1–10]. The gases and vapors produced during laser tissue interaction consist of [5]:

- combustion degradation gases, such as carbon dioxide (CO_2), carbon monoxide, hydrogen sulfide, and ammonia;
- volatile organic compounds, such as toluene, styrene, methylpyrazine, benzaldehyde, indol, skatol, phenol and benzyl cyanide;
- volatile organic compounds, such as formaldehyde, benzene, ethanol, carbon disulfide, well known as carcinogen.

Aerosols, vapors and gases in the surgical smoke produced during laser vaporization of the tissue may constitute a threat to personnel and the patient health and can be a potential risk. Besides the health risks due to the volatile organic compounds, particulate matter and tissue fragments ejected into the atmosphere can be inhaled and represent an additional risk. The noxious odor of surgical smoke is an indication of the content of the smoke. The smell is a conglomeration of chemical by-products from the burning of proteins and lipids when using laser or electrosurgical instruments [6, 7].

The surgical smoke containing aerosols and tissue fragments has been shown to be a viable transport mechanism for viruses, blood and cells [1–10]. Although rare, there have been reports of diseases transmitted from the patient to the surgeon *via* surgical smoke [2, 3]. From the health and safety perspective, the chemical, biological and particulate compositions of surgical smoke are therefore of great interest.

Laser photoacoustic spectroscopy (LPAS) is a sensitive technique for detection and monitoring of trace gases at very low concentrations. The most important features for a gas sensor include high sensitivity and selectivity, large dynamic range, high accuracy and precision, good temporal resolution, ease of use, versatility, reliability, robustness, and multicomponent capability. In conjunction with tunable lasers, the *in situ* monitoring of many substances occurring at ppbV (parts per billion by volume) or even pptV (parts per trillion by volume) concentrations is a routine task today. The photoacoustic (PA) detection provides not only high sensitivity, but also the necessary selectivity for analyzing multicomponent mixtures by the use of line-tunable IR lasers, as, for example, the CO_2 laser [11–17].

The CO_2 laser is of special interest, as it ensures high output power in a wavelength region where more than 200 molecular gases of environmental concern for atmospheric, industrial, medical, military, and scientific spheres exhibit strong absorption bands. This laser can be only stepwise tuned when operated in CW, and is an ideal source to push the sensitivity of photoacoustic gas detection into the concentration range of ppbV or even lower. Our photoacoustic system is adaptable with minor modifications to a broad range of gases and vapors having absorption spectra in the infrared region [11–16].

In this paper we present a study of chemical composition (six gases) of surgical smoke produced *in vitro* by irradiation of fresh animal tissue using a CO_2 laser in nitrogen atmosphere. Acetonitile, acrolein, ammonia, benzene, ethylene, and toluene were the gases that we determined using our CO_2 photoacoustic spectroscopy system. The influence of laser power, exposure time and the type of tissue on gas concentrations was investigated.

2. EXPERIMENTAL SECTION: LASER PHOTOACOUSTIC SPECTROSCOPY

Photoacoustic spectroscopy is an indirect technique by which, instead of direct measurement of light absorption, a side effect of absorption, the acoustic waves produced after local heating is measured. The photoacoustic response is fast, and due to the high sensitivity in trace gas detection there is no need of large quantity of sample. Spectral dependence of absorption determines the nature of components, allowing simultaneous measurement of different gas concentrations in gas mixture. The proportional PA signal depends linearly on the absorption coefficient and gas concentration. The block diagram of the laser photoacoustic spectrometer is shown in Fig. 1. The CW, tunable CO_2 laser beam is chopped, focused by a ZnSe lens, and introduced in the PA cell. Inside the PA cell the radiation produces pressure modulation recorded by sensitive miniature microphones as an acoustic signal. This acoustic signal is transmitted to a lock-in amplifier. After passage through the PA cell, the power of the laser beam is measured by a laser powermeter Rk-5700 from Laser Probe Inc. with a measuring head RkT-30. Its digital output is introduced in the data acquisition interface module together with the output from the lock-in amplifier. All experimental data are processed and stored by a computer.

The CO_2 laser used in this work is a high power laser (50 W, in order to obtain a smaller detectable trace gas concentration) GEM Select 50 Laser System, Coherent, Inc., tunable between 9.2 and 10.8 μm on 73 different vibrational rotational lines. The kind and number of detectable substances is related to the spectral overlapping of the laser emission with the absorption bands of the trace gas molecules in the wavelength region 9–11 μm. Thus, the accessible wavelength range, tunability, and spectral resolution of the laser are of prime importance. If there is a complex mixture of gases, one should choose a proper absorption line for determination of concentration, where line overlapping with other gases is low [11–14]. 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. So, we chose for each gas the corresponding laser line with the highest absorption coefficient (Table 1).

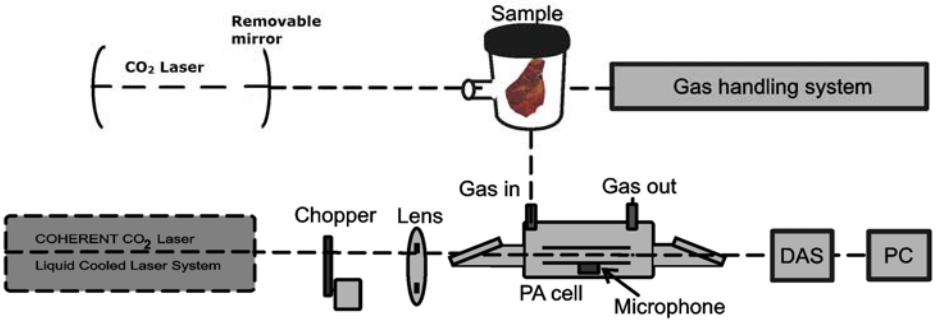

Fig. 1 – The CO_2 laser photoacoustic scheme.

Another important part is the gas vacuum/handling system which ensures gas purity in the PA cell. Due to the fact that water vapors and carbon dioxide are the principal components of surgical smoke and the CO_2 laser lines are slightly absorbed by these, it is necessary to introduce the potassium hydroxide (KOH) scrubber to remove most of the carbon dioxide and water vapors from the surgical smoke.

Tabel 1

Type of gases measured from surgical smoke with the corresponding laser line and the absorption coefficient

Gas	**CO_2 laser line**	**Wavelength [μm]**	**Absorption coefficients [cm^{-1} atm^{-1}]**
Acetonitrile	9P(16)	9.517	0.15
Acrolein	10R(14)	10.286	2.80
Ammonia	9R(30)	9.217	56.00
Benzene	9P(30)	9.636	2.00
Ethylene	10P(14)	10.529	30.40
Toluene	9P(28)	9.618	0.67

3. PRODUCTION AND COLLECTION OF SURGICAL SMOKE SAMPLES

Laser smoke was produced *in vitro* by ablation of fresh porcine tissues placed in a glass cylinder [14] provided with a ZnSe window, which is positioned perpendicular to the laser beam, and two access pipes for handling main gases connected to a gas system and to the PA cell. The laser vaporization of the tissues was realized in a closed environment in nitrogen atmosphere and the smoke was collected for photoacoustic measurements in the PA cell. The smoke was introduced into the PA cell using nitrogen gas *via* a regulator valve to maintain a constant flow at atmospheric pressure.

The influence of the main components of surgical smoke, water vapors and carbon dioxide was removed by introducing before the PA cell a KOH trap. The pellets of the KOH trap were replaced before every measurement and the PA cell was cleaned after each measurement, first by using a vacuum pump and then the stream of nitrogen (purity 99.999%). The measurements correspond to a dilution of the smoke sample in 1 dm^3 of buffer gas (nitrogen).

The surgical smoke samples were analyzed without using a particle filter, so the results could be somehow altered by the presence of smoke particles inside the PA cell. Measurements were realized at the atmospheric pressure (1010–1034 mbar) and room temperature (23 ^{o}C). As tissue samples we used pig skin, pig kidney, pig muscle, and pig heart that were stored at 4 ^{o}C until the moment of use. The porcine tissues were obtained from a local slaughterhouse.

With our photoacoustic system we determined the concentration of acetonitrile, acrolein, ammonia, benzene, ethylene and toluene. We investigated different types of tissue at a vaporization laser power of 10 W and 15 W, respectively, and exposure times of 5 s and 15 s, respectively. For each tissue type (pig kidney, muscle, skin and heart) we performed several measurements and the presented results are the average of the determined gas concentrations (given in ppmV).

4. RESULTS AND DISCUSSION: QUANTITATIVE ANALYSIS

The influence of laser power, exposure time and tissue type on the gas concentrations was investigated using the LPAS system. The surgical smoke was produced *in vitro* by CO_2 laser vaporization of porcine tissue in a closed environment. All gases (acetonitrile, acrolein, ammonia, benzene, ethylene and toluene) released from tissue samples were measured in the CO_2 laser wavelength range (9.2–10.8 μm).

The average gas concentrations measured in the smoke samples with our LPAS system are acetonitrile – 190 ppm, acrolein – 35 ppm, ammonia – 25 ppm, benzene – 20 ppm, ethylene – 0.410 ppm, and toluene – 45 ppm for kidney, muscle, skin and heart pig tissues, but gas concentrations may vary from sample to sample. The variations of gas concentrations for acetonitrile, acrolein, ammonia, benzene, ethylene and toluene with laser power, exposure time, and tissue type are presented in Figs. 2–7. We observe that the concentrations for all six gases increase with laser power and with exposure time and depend on the type of tissue sample. The higher concentrations were measured in pig skin sample. When pig heart is used as sample, we observed a different behavior of gas concentrations, as it can be remarked in Fig. 5.

In the case of tissue samples with a low percent of water, as pig skin sample, the gas concentrations (acrolein, benzene, and toluene) are greater than in the case of tissue samples with a high percent of water. This means that the humidity not only helps to estimate the role of the surrounding atmosphere, and reduces the concentration of hazardous chemicals, but it can be another way to reduce the emission of toxic substances during laser-tissue interaction. This result illustrates the role of water vaporization during laser irradiation of tissue. It is possible that during laser radiation interaction with a tissue that contains enough water; a water vapor cloud could be formed that screens the reaction of the surrounding

atmosphere. The water content of the tissue influences the emission of volatile organic compounds, and this can be observed especially in the case of benzene and toluene [18].

The difference in concentration could also be due to scattering on soot particles, because the measurements were made without a particle filter.

The medical personnel is exposed over a greater period of time to surgical smoke and the surgeons who work at a distance of 20–40 cm from the area of smoke generation are exposed to the highest concentration of smoke [3]. Standard surgical masks are inadequate to protect the medical personnel and the surgeon [9].

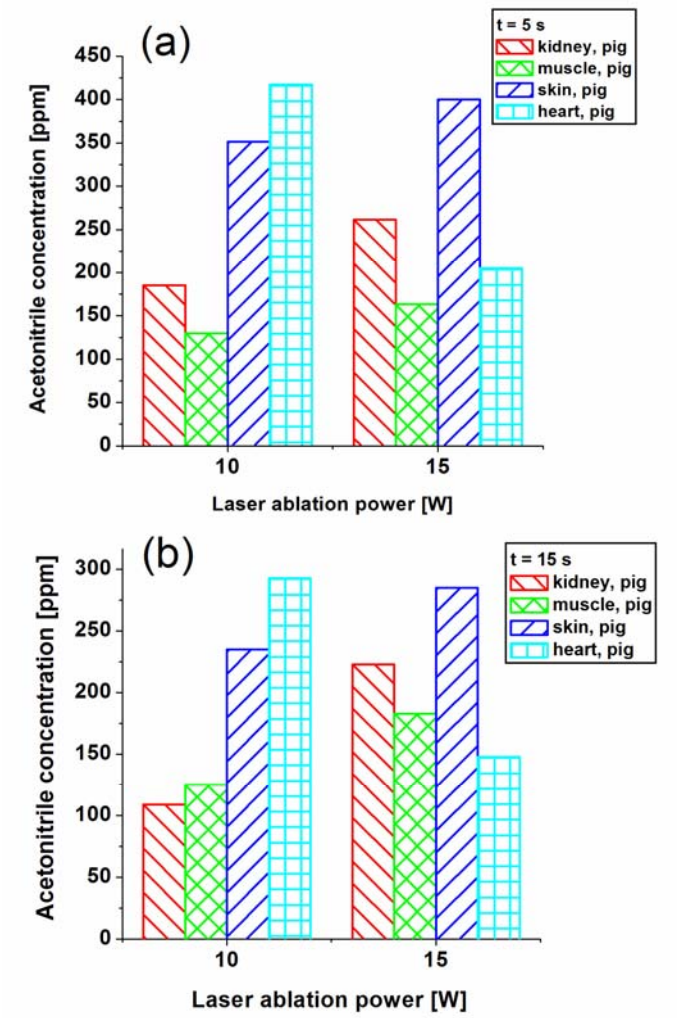

Fig. 2 – Gas concentration for acetonitrile at P = 10 W and P = 15 W for:
a) exposure time of 5 s; b) exposure time of 15 s.

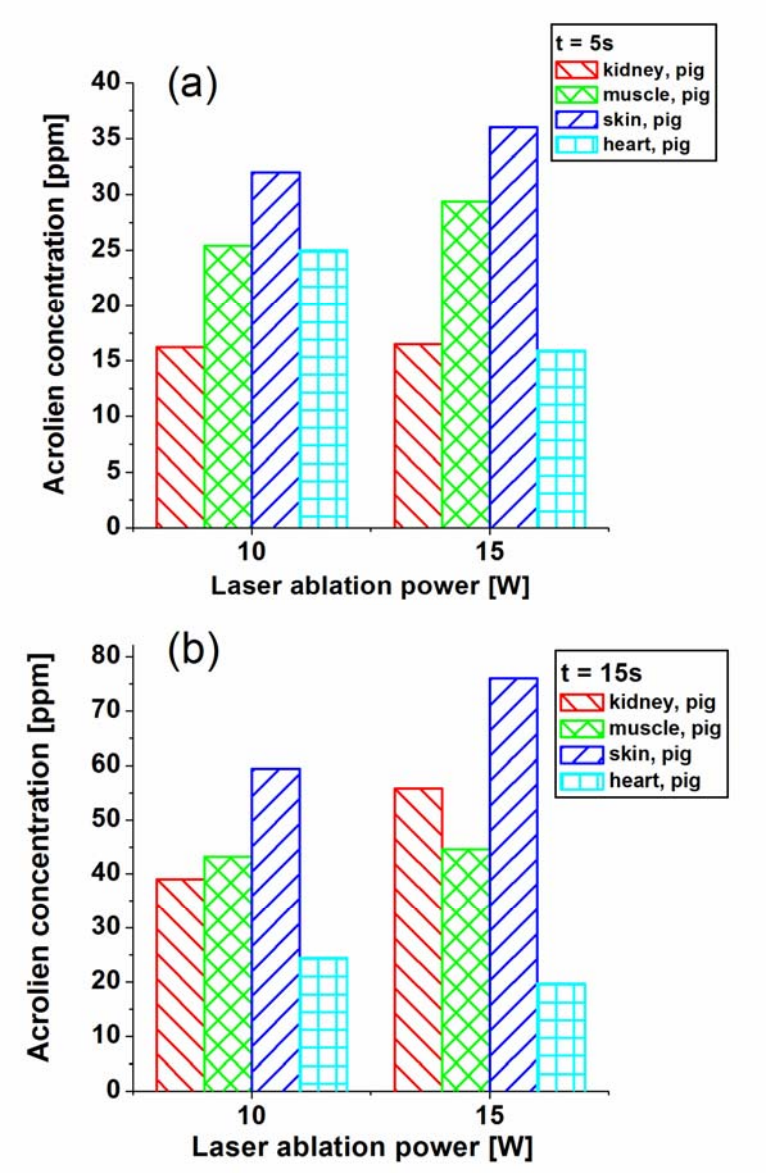

Fig. 3 – Gas concentration for acrolein at P = 10 W and P = 15 W for: a) exposure time of 5 s; b) exposure time of 15 s.

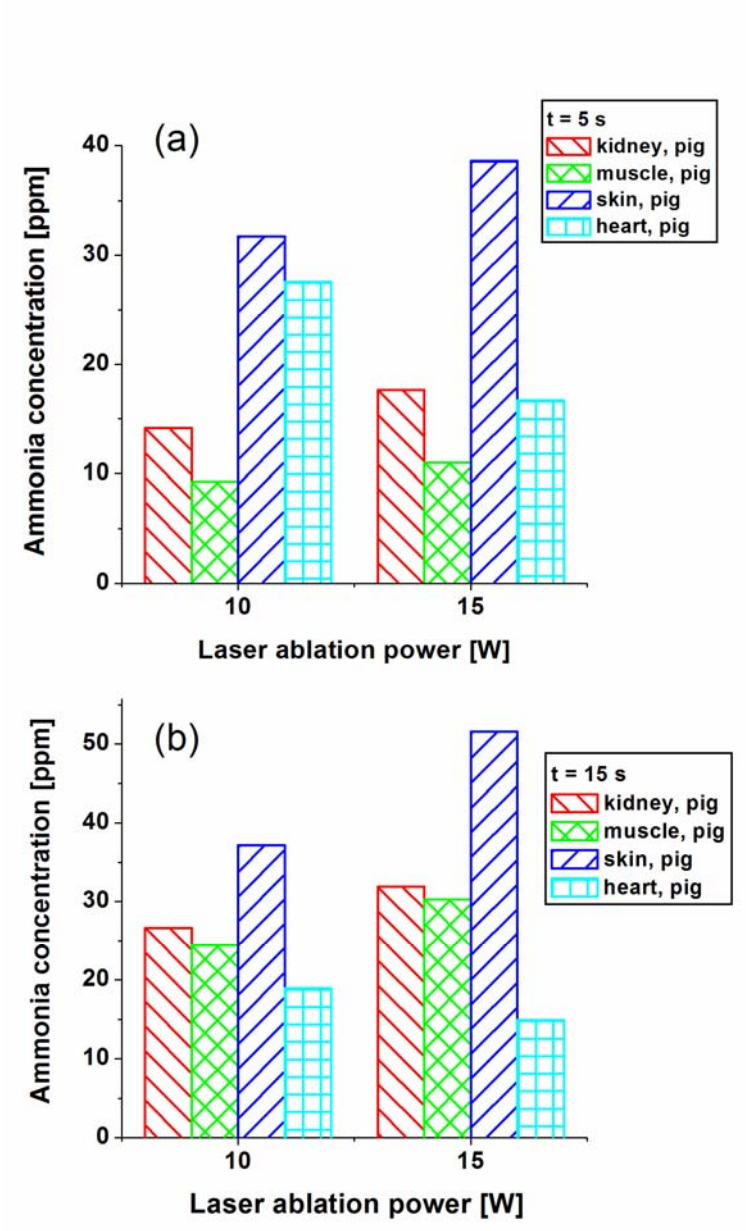

Fig. 4 – Gas concentration for ammonia at P = 10 W and P = 15 W for:
a) exposure time of 5 s; b) exposure time of 15 s.

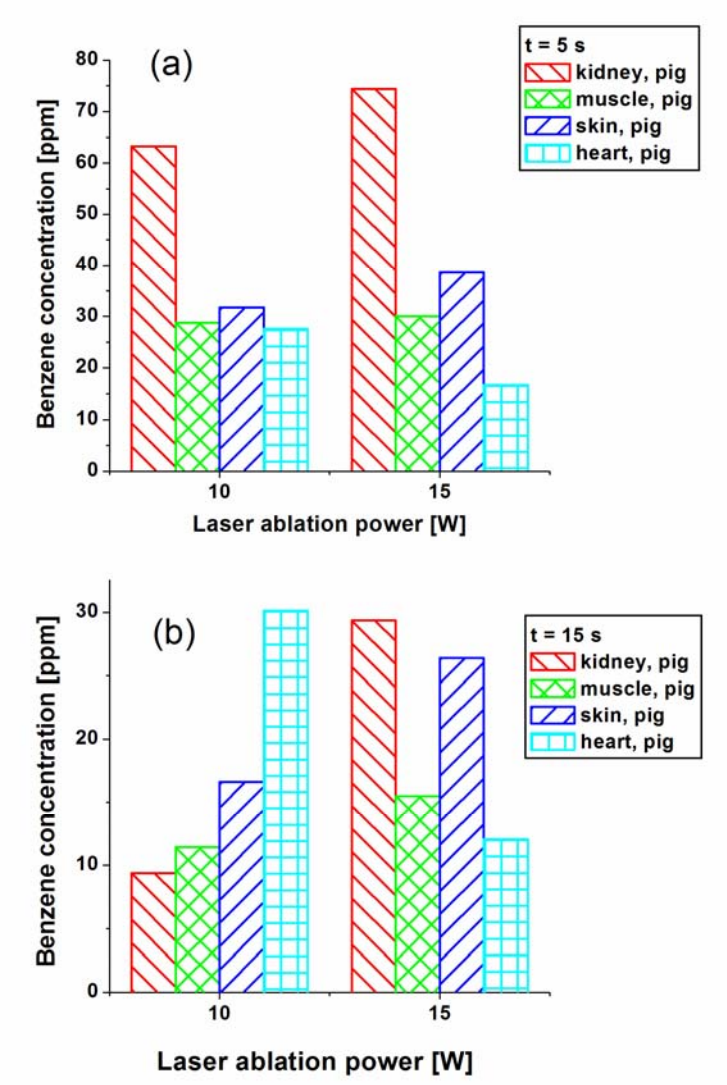

Fig. 5 – Gas concentration for benzene at P = 10 W and P = 15 W for: a) exposure time of 5 s; b) exposure time of 15 s.

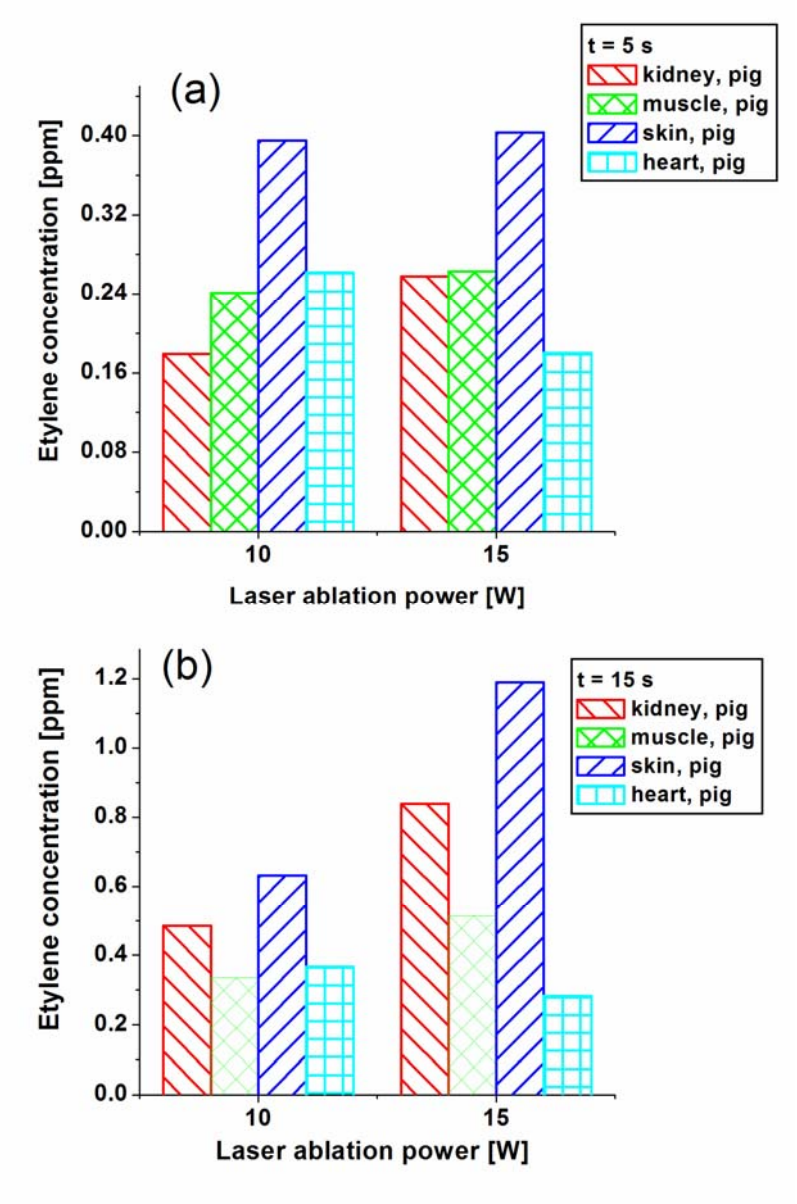

Fig. 6 – Gas concentration for ethylene at P = 10 W and P = 15 W for:
a) exposure time of 5 s; b) exposure time of 15 s.

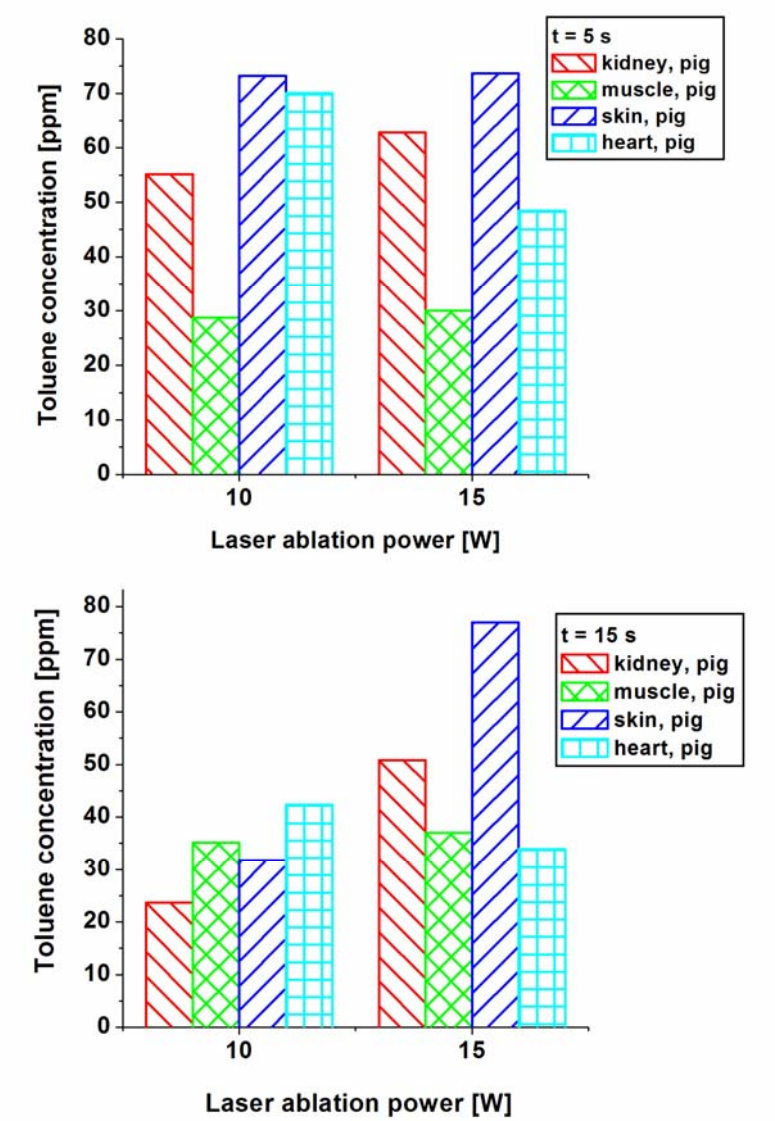

Fig. 7 – Gas concentration for toluene at P = 10 W and P = 15 W for:
a) exposure time of 5 s; b) exposure time of 15 s.

5. CONCLUSIONS

In the present study, a quantitative analysis of surgical smoke produced *in vitro* by irradiation of porcine tissues in a closed nitrogen atmosphere was made using a CO_2 laser photoacoustic spectroscopy system.

We demonstrated the presence of six toxic gases (acetronitrile, acrolein, ammonia, benzene, ethylene and toluene) in surgical smoke after laser vaporization at each measurement and the concentrations are of the order of ppmV.

These results demonstrate that the laser vaporization power and the exposure time are important parameters and gas concentrations are influenced by the water content of tissues. The toxic gas concentrations in smoke samples depend proportionally with the laser vaporization power and with the exposure time, but also depend on tissue type.

The results showed that the LPAS system proved its efficiency in analyzing a multicomponent gas mixture.

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