CARBON DIOXIDE AND WATER VAPORS DETECTION FROM SURGICAL SMOKE BY LASER PHOTOACOUSTIC SPECTROSCOPY

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Laser photoacoustic spectroscopy (LPAS) is a very powerful technique capable of measuring trace gas concentration from multicomponent mixtures with high accuracy. Technical details of the setup together with the latest performance parameters are presented. The real-time nature, high selectivity and sensitivity of LPAS detection allow the investigation of gases at low concentrations. New investigations based on LPAS technique have been performed to analyze carbon dioxide and water vapors from surgical smoke. We measured these two concentrations from surgical smoke produced by CO_2 laser ablation of fresh animal tissue in nitrogen or synthetic air. We found a concentration of water vapors from 1% to 11% and a concentration of carbon dioxide in the range of 1.34 ÷ 8.6%.

Keywords: Laser photoacoustic spectroscopy, photoacoustic cell parameters, surgical smoke, carbon dioxide, water vapors

1. Introduction

Biomedical applications have gained a significant attention in recent years because of an increased interest in human health. The potential risks associated with the emission of hazardous products emitted by surgical smoke are of high concern. Operating room (OR) personnel is exposed to surgical smoke daily. The risk of surgical smoke is due to the odor, size of particles and gas concentration. The great threat is represented by the toxins that cause the odor in surgical smoke. These toxins are released into the air when the tissue is vaporized by the laser beam. The smell is a combination of chemicals from the combustion of proteins and lipids when laser is used. Studies have shown that these chemicals cause headaches, eye, nose and throat irritation, as well as potential long-term effects [1-5]. Some of these toxic gases have already been shown to be carcinogenic, such as benzene, which has been documented to be a trigger for leukemia [2]. Benzene was found in surgical smoke in concentration well above the permissible limit [5, 6]. Beside benzene, during laser tissue ablation, the released chemicals include

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formaldehyde, acrolein, carbon monoxide and hydrogen cyanide. High concentrations of carbon dioxide are also potentially dangerous. Analysis of surgical smoke is important in evaluation of risk to at which the medical staff and the patients are exposed.

The CO_2 laser is used by various medical specialties to vaporize, ablate or cut tissue. The CO_2 laser produces light with a wavelength of 10.60 μm, where the laser energy is highly absorbed by water and by all biological tissues with rich water content. When the absorbed laser light heats the tissue to approximately 100°C, vaporization of intracellular water occurs. This produces vacuole formation, cratering, and tissue shrinkage. As the CO_2 laser beam comes into contact with the tissue, the temperature rises and causes boiling the intra- and extracellular water. The cell expands due to steam formation, and explodes. The contents are released as steam and smoke. Surgical smoke is made of chemicals, blood, tissue particles, viruses, bacteria and consists mostly of water vapor and carbon dioxide [7].

The size of particles formed varies between over 200 μm and less than 10 nm. The mean diameter of particles depends in particular on how intensely the energy applied acts on tissues. The mean diameter of particle from surgical smoke after laser ablation is ~ 0.3 μm [8]. The effect of surgical smoke is estimated from its composition and the noxious nature of its components.

The monitoring strategy consists of carbon dioxide and water vapors measurements by LPAS. This technique has great potential to detect some of these gases due to its intrinsically high sensitivity, the large dynamic range, real-time data analysis and operational simplicity. LPAS is the most used method in monitoring trace gases at low concentration, even at ppbV level (parts per billion volume). Photoacoustic (PA) detection provides also the necessary selectivity for analyzing multicomponent mixtures by the use of line-tunable CO_2 lasers. 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 [9-16].

Even if the resolution of LPAS method is well above the necessity to measure concentrations of carbon dioxide and water in percentage values, our choice was based on the very low cost per test, both in time and consumables, on the use of a CO_2 laser source also for tissue irradiation, and most important, to the fact that other trace gases at ppb level were monitored in the same time.

2. Characterization of LPAS system

LPAS is based on the generation of an acoustic wave in a gas excited by a modulated laser beam. Laser radiation is modulated at a wavelength that overlaps with the spectral feature of the target species. In the PA cell, a fraction of the ground-state population of the target molecules is excited by absorption of the incident laser radiation.

Energy exchange processes occur between vibrational levels and from vibrational states to rotational degrees of freedom. The energy which is absorbed by a vibrational-rotational transition is almost completely converted to kinetic energy by collisional de-excitation of the excited state. The kinetic energy is then converted into a periodic local heating at the modulation frequency. Expansion and contraction of the gas in a closed volume give rise to pressure variation which is an acoustic wave measurable with sensitive microphones [17-21].

LPAS system has been described in detail in former published papers [21- 25] and is schematically represented in Fig.1.

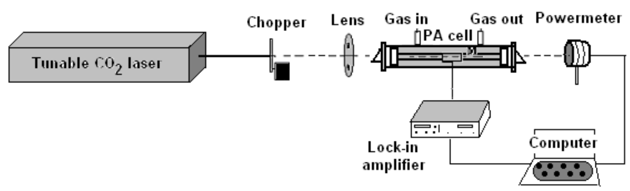

Fig.1. Schematic representation of the LPAS detector

The detector mainly consists of a line-tunable, frequency-stabilized CO_2 laser and a sensitive PA cell, in which the gas is detected. CO_2 laser beam is modulated by a mechanical chopper, focused by a ZnSe lens and enters via an IR-transparent window in the PA cell, where is locally absorbed by IR active molecules. Pressure wave generated are measured with sensitive miniature microphones. After passage through the PA cell, the power of the laser beam is measured by a laser radiometer. Its digital output is introduced in the data acquisition interface module together with the output from a lock-in amplifier. All experimental data are processed and stored by a computer.

An optimum acoustically resonant PA cell is used in our system. PA cell is made of stainless steel and Teflon to reduce the outgassing problems and consists of an acoustic resonator (pipe), windows, gas inlets and outlets, and microphones. A detailed description of our PA cell in presented elsewhere [21]. Inside the cell, these four microphones (sensitivity of 20 mV/Pa each), connected in series are mounted flush with the internal surface of the resonator tube. They are situated at the loops of the standing wave pattern, at an angle of 90^o to one another. The microphones are coupled to the resonator by holes (1 mm diameter) positioned on the central perimeter of the resonator.

A special consideration is given to the system parameter characterization when microphones of the PA cell were replaced with a newer version (Knowles electret - EK-23024) and new data were obtained. Microphone inlets were increased for the introduction of isolation between microphone case and resonator tube. From a bunch of 20 microphones, 4 with electrical impedance characteristics approximately equal were selected. Microphone cases were covered with isolator varnish. Microphones were then placed in Teflon holders and have been arranged tangentially to the inner surface of the resonator tube.

The position of the microphones inside the resonant tube was optimized by exciting the microphone–tube assembly using an acoustic signal provided by an audio generator equipped with a loudspeaker and following the signal response. Microphone positions were optimized one by one and then connected in series by recording the signal with a digital oscilloscope. After optimization of the signal from the 4 microphones, the optimum resonance frequency was measured under normal atmospheric conditions and the frequency was found around 560 Hz.

When the cell was filled with pure N_2 at atmospheric pressure, we measured the acoustic background noise (V_N^{ac} = 1.5 μV) and the photoacoustic background signal (V_N^{b} = 2.8 μV/W). In order to determine all PA cell new parameters, we performed a calibration of the PA system with a reference gas (1ppm ethylene in nitrogen) and found responsivity (R) of 433 cmV/W.

Based on the measured noises, background signals, and cell responsivity, all parameters characterizing the PA system can be evaluated. The methodology of all calculus was explained elsewhere [21, 24].

Table 1

PA system parameters.

Resonance frequency, f_0 (Hz)	564
Quality factor, Q	16.1
Cell responsivity, R (cmV /W)	433
Microphone responsivity, S_M (V/Pa)	$4x20x10^{-3} = 8x10^{-2}$
Cell constant, C (Pa cm/W)	$5.41x10^{3}$
Pressure amplitude response, p/P_L (Pa/W)	$1.57x10^{-1}$
Limiting sensitivity of the cell, S_{cell} (W cm^{-1})	$9.8x10^{-9}$
Limiting sensitivity of the system, S_{sys} (cm^{-1}) (at 3.92 W laser power)	$2.5x10^{-9}$
Limiting measurable concentration of ethylene, c_{lim} (pptV)	82
Minimum measurable signal in nitrogen, V_{min} (μV) (root mean square)	11
Minimum detectable pressure amplitude, p_{min} (Pa)	$3.87x10^{-4}$
Minimum detectable concentration, c_{min} (ppbV)	0.6

Minimum detectable absorptivity, α_{min} (cm^{-1})	$1.8x10^{-8}$
Minimum detectable absorption cross-section per molecule, σ_{min} (cm^2)	$7.2x10^{-28}$
Cell sensitivity for 1 ppbV of C_2H_4 at 1W of unchopped laser power, V_{ppb} (µV at 1 ppbV)	4.6

The outstanding features of the PA cell (small size, simplicity, and robustness) cannot be fully utilized unless it is combined with a suitable laser source. The laser source employed in our set-up is a homebuilt CO_2 laser that emits continuous wave radiation, is tunable between 9.2 and 10.8 µm on 62 different vibrational-rotational lines with an output power of 2-7 W.

Another important element in LPAS system is the vacuum/gas handling system. The Teflon/stainless steel system can perform several functions without requiring any disconnection. It can be used to ensure PA cell and gas purity, to pump out the cell, to introduce the sample gas in the PA cell at a controlled flow rate, and monitor the total and partial pressures of gas mixtures. The gas handling system consists of gas transport lines, three Baratron pressure gauges, two gas flow controllers, sample bag/cell and a KOH scrubber (when is needed). The design and importance of the system were explained in a previous paper [21].

3. Results

We present now the results of quantitative analysis of trace gas concentrations of carbon dioxide and water vapors from surgical smoke using a CO_2 laser photoacoustic system. The requirement for the gases to be detected is that they should possess strong characteristic absorption features in the wavelength range of the CO_2 laser, so we chose for carbon dioxide and water the corresponding laser lines with the highest absorption coefficient (see Table 2).

Table 2

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

Type of gas	CO_2 laser line	Laser line power [W]	Line wavelength [µm]	Absorption coefficient [$cm^{-1}atm^{-1}$]
CO_2	9R(18)	2.5	9.3	$3x10^{-3}$
H_2O	10R(20)	4.5	10.24	$8.3x10^{-4}$

We designed and built a simple glass cell that allows the cauterization of small pieces of animal fresh tissue (see Fig.2) [6]. Surgical smoke was produced *in vitro* by irradiation of fresh animal tissue with a CO_2 laser. The tissue samples used were procured from a local company processing the meat according to the EU standards. Ablation of tissue probes using a CO_2 laser was performed at different laser powers and different irradiation times. A gas of choice (nitrogen or synthetic air) was pumped into the cell glass through the gas inlet, while the produced smoke was transported through the gas outlet into the PA cell. Operating the PA cell at atmospheric pressure necessitates approximately 1000 cm^3 of flow gas in order to fill the internal volume of the cell. Hence, our measurements correspond to a dilution of the smoke sample in 1 dm^3 of buffer gas (nitrogen or synthetic air). Before reaching the PA cell, surgical smoke passes through a filter that retains particles with a diameter higher than 10 µm. Measurements were realized at the atmospheric pressure (1024-1034 mbar) and room temperature.

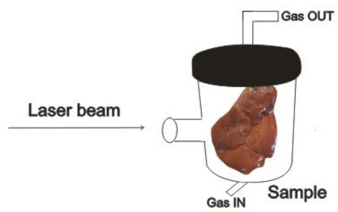

Fig.2. Glass cell used to obtain surgical smoke and connections to the PA cell.

The water vapors are a vehicle for other components [8]. Water vapor itself is not harmful, but acts as a carrier, and easily passes through the smoke evacuator and filter. In our measurements, water vapor percentage ranges between 1 and 11% (see Table 3), with lower concentration in tissue skin. It was observed that the percentage of water from surgical smoke increases with the laser power and the exposure time and depends on the type of tissue.

Like any other combustion, surgical interventions with laser produce carbon dioxide, carbon monoxide, as well as ammonia [5]. These substances are respiratory tract irritants and can cause effects related to tissue hypoxia. The carbon dioxide found in our measurements after CO_2 laser ablation of fresh animal tissue was in high concentration, in the range of 1.34% ÷ 8.6% (see Table 3). We observed an increase of concentration with the exposure time, in both nitrogen and synthetic air. High concentration of carbon dioxide in confined areas can be potentially dangerous. Carbon dioxide may act as an oxygen displacer and causes a number of reactions. These reactions may include dizziness, disorientation, and suffocation. An increase in inhaled carbon dioxide and subsequent reaction with water in the blood form carbonic acid (H_2CO_3) which dissociates into hydrogen ions (H^+) and bicarbonate (HCO_3) and the dissociation of carbonic acid increases the acidity of the blood (low pH) [5,8].

Table 3

Quantitative results of carbon dioxide and water in surgical smoke obtained from CO_2 laser ablation of fresh animal tissue.

Tissue	**Laser power-P [W]**	**Exposure time-t [sec]**	**CO_2 [%]**	**H_2O [%]**	**Atmosphere**
Spleen, pig	6	12	3.03	3.10	synthetic air
Spleen, pig	6	20	7.45	9.20	synthetic air
Spleen, pig	6	20	5.8	6	nitrogen
Lung, pig	6	12	1.34	1.9	nitrogen
Lung, pig	10	6	1.15	8	nitrogen

Liver, pig	10	3	2.43	3.7	nitrogen
Liver, pig	15	3	5.8	6.4	nitrogen
Skin, pig	15	3	6.32	1.35	nitrogen
Liver chicken	15	3	6.86	3.15	nitrogen
Kidney, pig	15	3	6.16	3	nitrogen

From these results we observed that the water vapors percentage depends also on the type of tissue. For example, the skin, which is a biological tissue with a low percent of water, has a lower percent of water vapors in surgical smoke.

4. Conclusions

The selected LPAS technique for trace gas analysis has a great potential in many clinical and biological disciplines and in health and safety monitoring.

We realized a quantitative analysis of carbon dioxide and water vapors released in surgical smoke obtained after CO_2 laser ablation of different fresh animal tissue with a CO_2 laser photoacoustic system. Future work is intended in order to establish the correct correlation of carbon dioxide and water quantities with the ablation conditions (laser power, interaction time, ablated volume).

Water vapor is the main component of surgical smoke, although it depends on the nature of the tissue, while carbon dioxide concentration depends of laser power and exposure time. The results may differ depending on laser power, exposure time, tissue selected and environment.

The values for carbon dioxide and water vapor concentrations were obtained from direct measurements inside the PA cell and not from open spaces, where gas concentrations from the surgical smoke is lower owing to dilution in air.

Due to the high concentration of carbon dioxide and water vapors in surgical smoke, and because the CO_2 laser lines are absorbed by these gases, for measurements of other components in surgical smoke it is necessary to introduce the KOH trap to remove significantly these interfering gases.

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