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Human Sinus Studies using Monte Carlo Simulations and Diode Laser Gas Absorption Spectroscopy

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Abstract—We demonstrate the possibility of non-intrusive in-vivo human sinus studies by diode laser gas absorption spectroscopy. Molecular oxygen in tissue-like phantoms were investigated in a practical backscattering detection geometry for frontal sinus studies both experimentally and numerically using the Monte Carlo concept, implemented in the Advanced Systems Analysis Program (ASAPTM) software. Light was launched into and detected from the forehead on a health volunteer. A model representing the frontal sinus measurements was implemented in ASAPTM and studied. The results from the experiments and the simulations show a good agreement for both the tissue-like phantom measurements and the measurements of the healthy volunteer. Preliminary data from human maxillary sinus measurements are also shown. The results are promising and suggest further development of this technique for sinuses studies.

I. INTRODUCTION

Within the bones of the human skull and face some air-filled cavities called the paranasal sinuses are located. The paranasal sinuses are connected to the nasal cavity through small orifices called ostia, which allow drainage and exchange of air, liquid and mucus. So far no one has convincingly been able to demonstrate any important physiologic function of the human sinuses. Different hypotheses on the possible functions have been proposed such as reduction of the skull weight, heat insulations, and increasing resonance of the voice. It seems like the only important aspect of the sinuses that everyone can agree upon is to make sure that they are kept free from diseases such as infections [1].

Sinusitis is an inflammation of the paranasal sinus mucosa, which is treated with antibiotics and often followed by one week of sick-leave. Every year, more than 37 million people in the US are diagnosed with sinusitis. Today, the diagnosis of sinusitis is mostly based on the anamnestic history of the patient, and in some cases on paraclinical investigations such as X-ray, ultrasound, and low-dose computerized tomography. Unfortunately, unnecessary antibiotic treatment is very common due to the difficult diagnosis. Therefore, there is a great need for simple, non-intrusive alternatives or complementary methods to detect sinusitis [2], [3].

In the present study we investigate the feasibility of using

diode laser gas absorption spectroscopy for sinusitis diagnostics on the frontal sinuses, located within the frontal bone. The experimental method presented is based on the sharp spectroscopic absorptive imprint of molecular oxygen in the air filled cavities. A backscattering detection geometry is used where narrow-band diode laser radiation is launched through the facial skeleton to transverse the frontal sinus cavities in the forehead. The light is then diffusely scattered in the deeper lying tissues with part of the light again traversing the cavities, and again scattered in the facial tissue to reach an external detector [4]. The light propagation of the experiment is also simulated [5] by using the Monte Carlo concept, implemented in the Advanced Systems Analysis Program (ASAPTM) software. Simulations and experimental data have been compared for a model based on two scattering bodies representing human tissue, with an air gap in between representing the sinus cavity. Finally, we have explored the possibility of performing imaging measurements of the frontal sinuses. The results of the simulations have been compared with results from measurements on the frontal sinuses of a healthy volunteer. Preliminary data have also been recorded on the maxillary sinuses, located within the cheekbone, of a healthy volunteer.

In the next section we describe the tools used in the study, which include the experimental setup, the computer simulations and the sinus models investigated in the latter. Experimentally obtained data are then compared with simulations. Finally, conclusions are drawn.

II. TOOLS USED

A. Experimental setup

The gas detection setup used in this study performs absorptive laser spectroscopy of diffusely scattered light. A schematic diagram of the setup is shown in Fig. 1. A diode laser, operating around 760 nm with an output of about 7 mW, is tuned across the R7R7 absorption line of molecular oxygen by supplying a saw-tooth ramp at 4 Hz to the laser driver current. A sinus-wave at 9 kHz is superimposed to the ramp in a wavelength modulation scheme to allow sensitive lock-in detection. The light is focused into a fibre guiding the light to

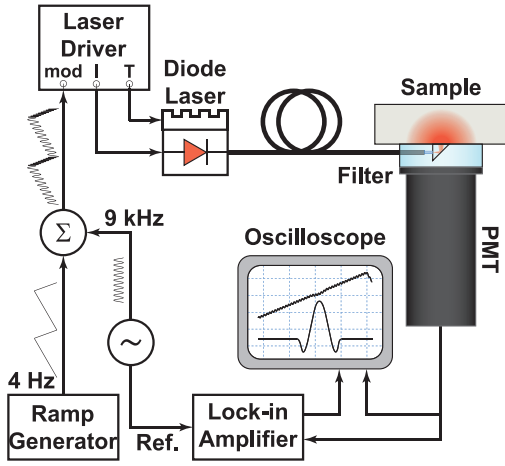


Fig. 1. Schematic drawing of the experimental arrangement for diode laser gas absorption spectroscopy in a backscattering detection geometry [4].

the sample. A small right-angle prism is positioned in front of the fibre centrally located to the detector and allowing the launching of the photons into the sample. An annular aperture, with an inner diameter of 10 mm and outer diameter of 21 mm is used to select backscattered photons. A blocking colored glass filter is placed above the detector protecting the detector from visible stray-light diluting the signal with noise. A photomultiplier is used as a detector providing efficient photon collection. The experimental setup is described in more details in Ref. [4].

The signal from the detector is divided into two parts. One part is directly sent to a computer controlled digital oscilloscope, referred to as the direct signal. The other part is sent to the oscilloscope via a lock-in amplifier where phase-sensitive detection at twice the modulation frequency is performed. This signal is referred to as the 2f signal.

The gas content in the sample is estimated using the Beer-Lambertian law, stating that for small absorptions the fractional absorption is proportional to the gas concentration. Hence, the 2f signal is normalized to the amount of light reaching the detector (the direct signal). To estimate the gas content in the sample, the peak-to-peak value of the normalized 2f signal is then estimated.

A method called standard addition was used to calibrate the obtained normalized peak-to-peak value and to transform it to a more meaningful quantity, a so-called equivalent mean path length L_{eq} , described in Ref. [4]. The method is based on adding known path lengths of air to the scattering sample and measuring the normalized peak-to-peak values. The values are then plotted as a function of added air and are expected to fall on a straight line. The zero crossing yields the $\langle L_{eq} \rangle_{exp}$. In other words, L_{eq} corresponds to how far the light has to travel in ambient air to obtain the same normalized peak-to-peak value. This is described in (1), where c_{air} corresponds to the gas concentration in ambient air, $\langle L_{sample} \rangle$ to the mean path length in the sample, and c_{sample} to the gas concentration

in the sample.

$$\langle L_{eq} \rangle_{exp} \cdot c_{air} = \langle L_{sample} \rangle \cdot c_{sample} \quad (1)$$

It should be noted that the obtained L_{eq} value is dependent of both the gas concentration and the scattering properties of the medium.

B. Simulations

The simulation performed in this study is based on the Monte Carlo concept, implemented by the ASAPTM software [7]. Monte Carlo is a statistical method and the basic idea is to launch a large number of photons into the sample where each photon experiences an individual random walk through the sample based on its optical properties [8].

By studying the rays reaching the detector in the simulations, the equivalent mean path length, $\langle L_{eq} \rangle_{sim}$, could be calculated for all models used in the study. For every ray ASAPTM computes information such as the flux at every surface it enters or gets reflected off, as well as the distance it has traveled in all media. We then calculate $\langle L_{eq} \rangle_{sim}$ by adding up, for all rays, the product of the distance, L , each individual ray has traveled in the air space and its corresponding flux, ϕ , when reaching the detector, and dividing it by the total flux reaching the detector. This is described in (2) where n is the total numbers of rays reaching the detector.

$$\langle L_{eq} \rangle_{sim} = \frac{\sum_{i=1}^n L_i \cdot \phi_i}{\sum_{i=1}^n \phi_i} \quad (2)$$

C. Frontal sinus models

The tissue-like phantom model used in the simulations and the experiments is shown in Fig. 2, symbolizing measurements on the frontal sinuses. Two white Delrin-type plastic blocks were used, denoted primary scatterer S_1 and secondary scatterer S_2 , respectively, with thickness l_1 and l_2 , respectively, with optical properties similar to human tissue. A variable air gap was placed in between the blocks to represent measurements of the human frontal sinuses. In the simulations the optical properties of the scattering material were set to $g=0.87$, $\mu_s=14 \text{ mm}^{-1}$, and $\mu_a=0.0005 \text{ mm}^{-1}$, which were measured for one of the Delrin plate using the integrating-sphere technique [9].

To investigate the feasibility of imaging of the frontal sinuses, a new model was created and implemented in ASAPTM. The sinuses in the model were represented by two ellipsoids (25 mm high, 20 mm wide, 10 mm deep) embedded at a depth of 10 mm in a scattering medium, with optical properties set to $g=0.87$, $\mu_s=16 \text{ mm}^{-1}$, and $\mu_a=0.0005 \text{ mm}^{-1}$ [6]. The dimensions of the ellipsoids as well as the location and optical properties of the scattering medium are chosen to mirror reality.

The backscattering detection geometry used in the experiments was also included in the two models studied. In Fig. 2 the different parts of the detection can be seen. Like in the

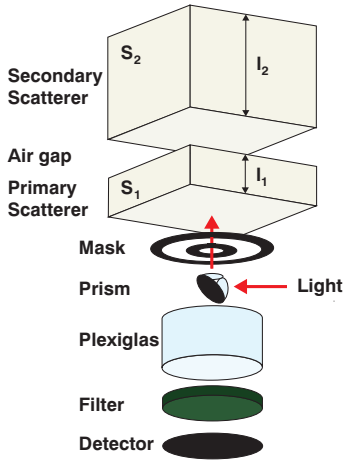


Fig. 2. Phantom models used in experiments and simulations representing measurements on the human frontal sinuses with a backscattering detection geometry [4], [5].

experiments, the photons were selected in the simulations by an annular aperture, with an inner diameter of 10 mm and outer diameter of 21 mm.

III. RESULTS

Data obtained from experimental measurements and simulations from the tissue-like phantom are shown in Fig. 3. The influence of the air gap distance between the scatterers as well as the thicknesses of the scatterers has been investigated. In Fig. 3a l_1 has been kept constant to 3 mm and in Fig. 3b l_2 has been kept constant to 30 mm. As can be seen in the figures the agreement between the experiments and the simulations is very satisfying. In both simulation and experiment we observed an increase in the signal for an increase thickness of S_2 . Intuitively thus can be understood since S_2 allows more signal photons that have traveled over the air gap to be scattered back to the detector. An increase of the signal can also be seen for a decreasing thickness of S_1 . This behavior can be explained by the so-called "short-cut" photons, which are those photons that have never traveled over the air gap but only been scattered in S_1 before reaching the detector. These photons only contribute to the L_{eq} by a diluting factor. That the signal starts by increasing as the air gap increases and then falls off after a certain air gap value can be understood from the finite size of the detector. The signal behavior is explained in more detail in Refs [4] and [5], where the influence of the annular aperture of the detection geometry and the scattering properties of the two scatterers has also been investigated.

The frontal imaging simulations and the experimental results from measurements on the frontal sinuses of a healthy volunteer are shown in Fig. 4. The model used for frontal imaging simulations is shown in Fig. 4a, and in Fig. 4b the simulated L_{eq} for the model is presented. It can clearly be seen that the technique presented has the potential to spatially resolve the cavities. Fig. 4c shows measurements performed on the volunteer. About 10 measurements on and off right and left frontal sinus, respectively, were performed and an average

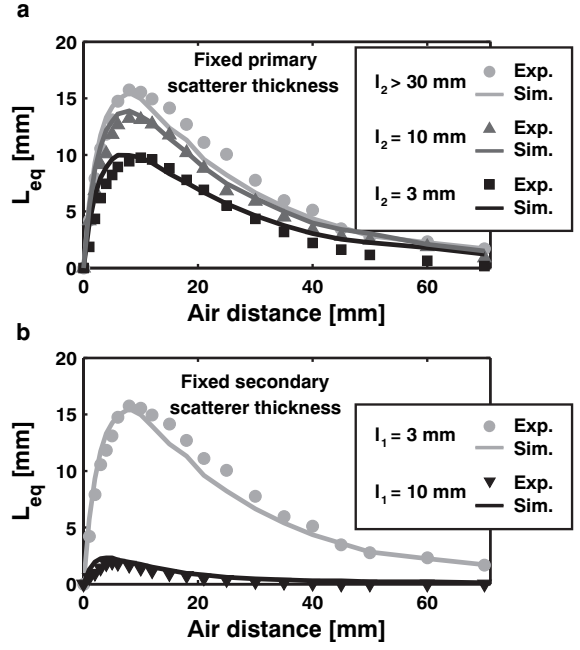


Fig. 3. The equivalent mean path length, L_{eq} , as a function of air gap distance in phantom experiments and simulations for the backscattering detection model shown in Fig. 2a, representing measurements on the human frontal sinuses. (a) Fixed primary scatterer thickness $l_1=3$ mm. (b) Fixed secondary scatterer thickness $l_2=30$ mm [4], [5].

of these measurements is presented. The measured L_{eq} values are in the same range as the simulated L_{eq} values.

Preliminary studies of the maxillary sinuses, in a transmission detection geometry, were also performed. The fibre was placed inside the mouth on the palate while the detector was positioned on the cheekbone. A larger L_{eq} is expected in this detection geometry since it avoids the problem of "short-cut" photons. Almost all photons detected must have traveled over the air-filled cavity and thus contain information about the gas of interest. An experimental curve recorded on a human maxillary sinus is shown in Fig. 5. It was recorded under very non-optimal conditions with a laser power of only 0.2 mW, and with extremely little light passing to the detector. The signal shown in the figure corresponds to an air path of about 25 mm, which is in agreement with expected size of the human maxillary sinus.

IV. CONCLUSION AND DISCUSSION

The presented study clearly shows the possibility of using the introduced diode laser absorption spectroscopy based technique for sinus studies. To investigate the clinical usefulness of the approach, measurements have to be performed on patients affected by inflammation and on healthy volunteers. The phantom studies have resulted in a better understanding of the possible signal behavior, which can be very valuable when performing further measurements on patients.

The experimentally obtained data and the simulated data for frontal sinus studies show a good agreement for both the tissue-like phantom measurements and the volunteer for

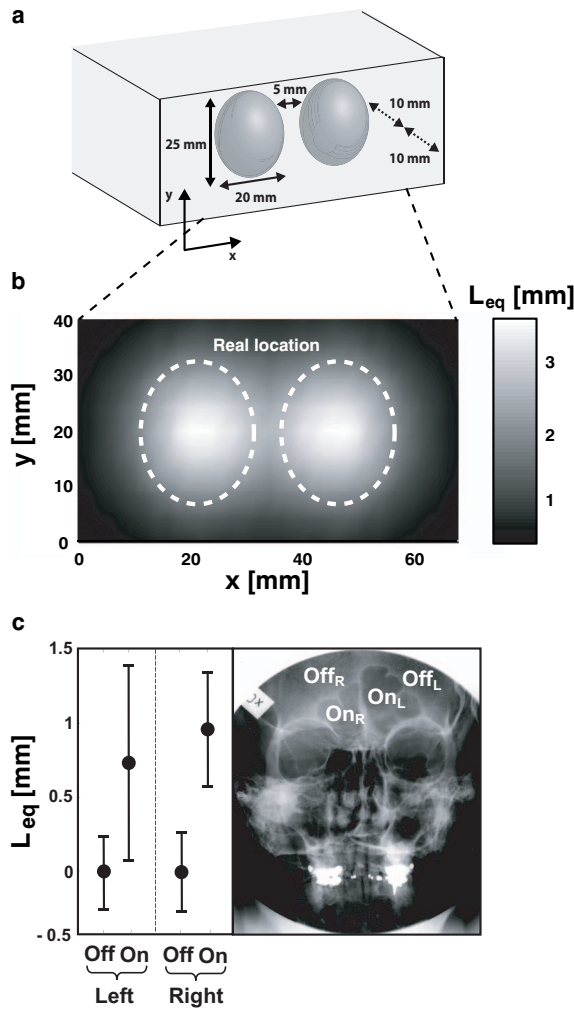


Fig. 4. (a) Model used in ASAPTM to simulate imaging of the frontal sinuses. (b) Simulated equivalent mean path length, L_{eq} , obtained when scanning over the model using backscattering detection geometry [5]. (c) To the left: The average L_{eq} from measurements on and off the frontal sinus on a healthy volunteer (as shown to the right) together with error bars corresponding to one standard deviation. To the right: X-ray image on the volunteer, showing the extent of the frontal sinuses [4].

the limited setup conditions studied so far. This has given us confidence in using simulation to further guide and optimize the technique presented. Our very preliminary data on human maxillary sinuses indicate that diagnostics in such locations should also be quite feasible.

As briefly mentioned in the introduction, sinusitis normally occurs via blockage of the small tubes connecting the sinuses to the nasal cavity. It might be possible to detect sinusitis at an early state by studying the gas transport between the nasal cavity and the sinuses. By inhaling another gas such as helium, the time-constant of the gas flow into the sinuses can be measured. If the channels are totally blocked, no change in the signal should be measured [4].

In the study presented, molecular oxygen has been studied. We recently showed a possibility of detecting two gases simultaneously, molecular oxygen at 760 nm and water vapor

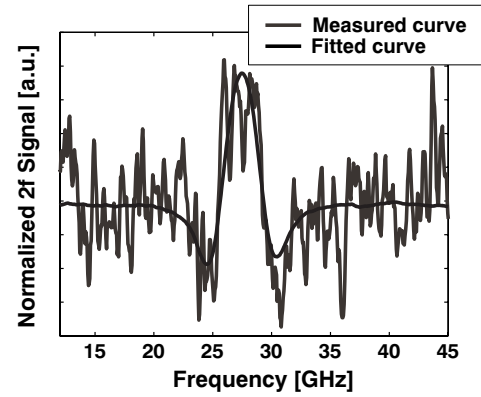


Fig. 5. Recorded normalized 2f signal, obtained due to molecular oxygen absorption, from measurements on a human maxillary sinus in a transmission detection geometry. The signal recorded corresponds to a L_{eq} value of about 25 mm.

at 980 nm, during the drying process of wood. By detecting two gases at the same time and creating the ratio of the two obtained L_{eq} values for the gases, the influence of the scattering properties of the sample could be neglected. This assumes that the scattering properties are about the same for the two wavelengths. This would then provide more reliable information on the actual gas concentration within the sinuses.

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