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Non-intrusive optical study of gas and its exchange in human maxillary sinuses

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ABSTRACT

We demonstrate a novel non-intrusive technique based on tunable diode laser absorption spectroscopy to investigate human maxillary sinuses *in vivo*. The technique relies on the fact that free gases have much sharper absorption features (typical a few GHz) than the surrounding tissue. Molecular oxygen was detected at 760 nm. Volunteers have been investigated by injecting near-infrared light fibre-optically in contact with the palate inside the mouth. The multiply scattered light was detected externally by a handheld probe on and around the cheek bone. A significant signal difference in oxygen imprint was observed when comparing volunteers with widely different anamnesis regarding maxillary sinus status. Control measurements through the hand and through the cheek below the cheekbone were also performed to investigate any possible oxygen offset in the setup. These provided a consistently non-detectable signal level. The passages between the nasal cavity and the maxillary sinuses were also non-intrusively optically studied, to the best of our knowledge for the first time. These measurements provide information on the channel conductivity which may prove useful in facial sinus diagnostics. The results suggest that a clinical trial together with an ear-nose-throat (ENT) clinic should be carried out to investigate the clinical use of the new technique.

Keywords: Diode lasers, Near infrared spectroscopy, Absorption, Molecular oxygen, Medicine, Human sinuses

1. INTRODUCTION

In addition to the mouth and nasal cavities, the human head comprises further air volumes, all connected to the nose and the epipharyngeal area by venting channels. The middle ear, the frontal and maxillary sinuses are such air-filled volumes that are all quite vulnerable to infection (conditions called otitis and sinusitis, respectively). The cavities may then be filled with swollen mucosa, mucus and pus, and treatment with antibiotics is frequently considered appropriate. Each sinus is connected by a channel with a mucous membrane lining to the nose for free exchange of air and mucus. Anything that causes a swelling in the nose such as an infection, an allergic reaction, or another type of immune reaction, can affect the sinuses. With any of these above mentioned conditions, these passages may be blocked. In view of the many million patients suffering from this type of infection, improved diagnostic tools, complementing or replacing ultra-sound and CT scans are desirable.[1–6]

Recently, we reported on a new technique for assessing the sinuses relying on the monitoring of the oxygen absorption at about 760 nm. The absorption features are more then a factor of 1000 sharper than the spectral signatures of the tissues. In the first study, a faint oxygen signal could be observed in a backscattering geometry for the frontal sinuses of a healthy volunteer.[7] We have now explored the technique in a transmission geometry probing the maxillary (cheek) sinuses by injection of light using fibre optics in contact with the palate, and detecting the diffusely scattered light emerging out through the cheek bone. Strong signal differences in oxygen imprint between two volunteers with widely different anamnesis regarding maxillary sinus status were observed. By improved handling of noise and detrimental interference fringes, we now obtained prominent signals, which also allowed a dynamic study of gas exchange through the venting channels. Sinus ventilation studies have previously been performed by radioactive tracer gases, such as Xe^{133}, in combination with single photon emission computed tomography (SPECT).[8] Another method attempted is to use stable xenon inhalation followed by computer tomography (CT).[9]

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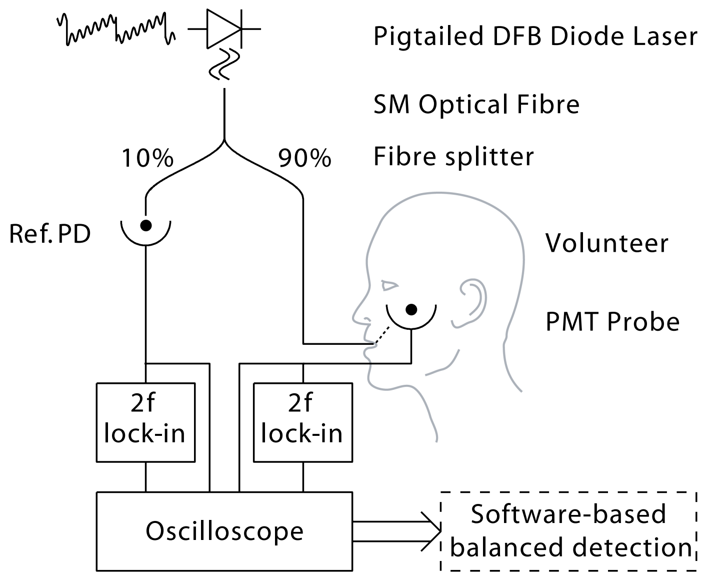

Figure 1. Schematic drawing of experimental arrangement for tunable diode laser gas absorption spectroscopy of oxygen probing the human maxillary sinuses.

In the following section the experimental setup, the data evaluation and the measurement procedure will be discussed. Results from two volunteers with widely different anamnesis regarding maxillary sinus status will then be shown. At the end conclusions of the presented work will be drawn. An outlook of future work will then be discussed.

2. MATERIAL AND METHOD

2.1. Experimental setup

A schematic drawing of the arrangement used in this study is shown in Fig. 1. The setup is based on a distributed feedback (DFB) diode laser that is single-mode (SM) fibre-pigtailed and thermoelectrically cooled (Nanoplus, Germany). The laser operates with an output power of about 4 mW. The light was scanned across the R11Q12 molecular oxygen absorption line at 760.445 nm (vacuum wavelength) by supplying a 4 Hz saw-tooth ramp to the laser driver current. A 9 kHz sinus-shaped wave was superimposed on the laser driver current in a wavelength modulation scheme to achieve sensitive detection.

The light from the fibre was split 90/10(%) with a single-mode fibre-coupled beamsplitter (Laser2000, Sweden) to allow balanced detection. The fibre carrying the lower intensity was directly guided to a photo diode, PD, (10DP/SB, OSI Optoelectronics), producing the reference signal. The other fibre part (90% of the intensity) was positioned on the palate inside the mouth. The light then travels through the tissue with a fraction part of it crossing the maxillary sinuses. The multiply scattered light was detected by a photomultiplier tube, PMT, (5070A, Hamamatsu) at different locations on the cheek bone by a handheld probe. This signal is denoted as the sample signal. The two signals were each split into two parts; one of the parts was directly connected to an oscilloscope remote controlled, called the direct signal, while the other parts was first sent via a lock-in amplifier (5209, EG&G Princeton Applied Research), where the 2f signal was detected.

2.2. Data evaluation

To suppress noise and perturbations, like optical interference fringes, software based balanced detection was used. These procedures have been described in detail elsewhere.[10] Briefly, the two detected 2f signals are first normalised with the direct signals. A set of parameters is then estimated by comparing the normalised reference signal and the normalised sample signal at frequency regions outside the expected oxygen imprint. A matched version of the reference signal is then subtracted from the sample signal over the whole frequency scan.

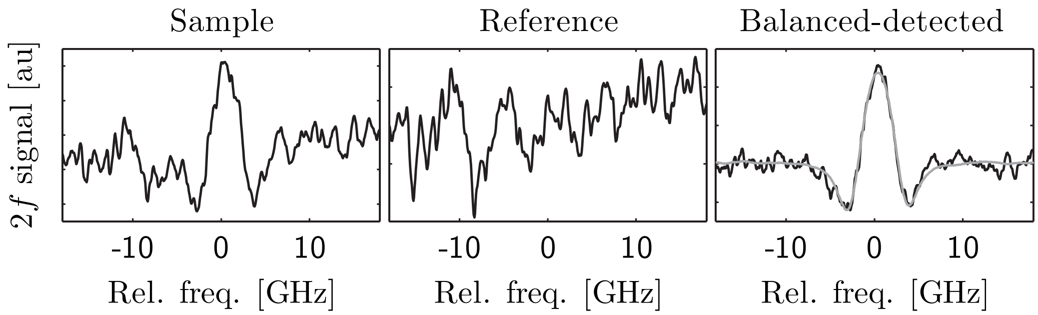

Figure 2. Typical recorded signals in this study from the sample detector (to the left) and the reference detector (center). The balanced-detection signal is also included with a fitted ideal function (to the right). The signal corresponds to an L_{eq} of 25 mm corresponding to an absorption fraction of $3.8 \cdot 10^{-4}$.

Once a balanced-detection signal is computed, an ideal signal is fitted to it. This signal obtained from a measurement where the oxygen imprint is many orders larger than the noise, created by measuring over an air distance of several meters. Fig. 2 shows typical recorded signals. To the left a signal from the sample detector is shown, in the center a corresponding signal from the reference detector is given, and to the right the computed balanced-detection signal is included together with the fitted ideal signal.

A quantity called the equivalent mean path length, L_{eq}, was estimated from the amplitude of the balanced-detection signal. This quantity corresponds to how far light has to travel in ambient air to achieve the observed absorption imprint. The calibration was done by employing the standard-addition method.[7,10] The signal shown in Fig. 2 corresponds to an L_{eq} of 25 mm. We note that the L_{eq} signals depend on the gas concentration as well as the effective light path way that becomes an undefined quantity in a scattering medium. However, as we shall see, this difficulty can be suppressed under certain conditions.

2.3. Measurement procedure

Measurements were performed on two volunteers; one with constantly recurring sinus problems (Volunteer I) the other one with no history of such problems (Volunteer II). A CT image of Volunteer I is shown in Fig. 3a. It can clearly be seen that the left maxillary sinus is completely filled with inflamed swollen mucosa while the right one is only partly filled.

Four different measurements are presented in this study and are listed below:

Signal levels: The L_{eq} was measured on both volunteers in the left and right maxillary sinuses. The fibre was placed on the palate inside the mouth in close proximity to the particular sinus. The light was detected at two different locations; on the cheek bone and translated towards the nose (about 2 cm). Measurements were performed once a day during about a week.

Control: Two types of reference measurements were performed to investigate any possible L_{eq} offset in the current setup. The signal was measured through the cheek and the hand of the volunteers. In the case of reference measurements through the cheek, the fibre was placed inside the mouth in contact with the cheek and the detector was positioned on the opposite side of the cheek. In the case of reference measurements through the hand, the fibre was placed in contact with the palm and the detector was positioned on the opposite side of the hand.

Reproducibility: The reproducibility of the measured L_{eq} values was also investigated for Volunteer II. 10 measurements were done on the each sinuses by removing the detector and fibre between each recording. Measurements were done for the both the detector positions explained above.

Gas exchange: To study the ostia function (ventilation between nasal cavity and sinus cavity) L_{eq} was measured continuously during inhalation of non-ambient air (pure nitrogen). Data was collected for about 3.5 min;

1 min before flushing with nitrogen, 30 s during nitrogen flush through the nostril and for about about 2 min after terminating the flush, all the time pursuing normal mouth breathing. Each recorded signal was averaged for about 15 s. Measurements were performed on both the left and right maxillary sinuses on Volunteer I and II.

3. RESULT

Signal levels

The average measured L_{eq} values from the two volunteers together with error bars corresponding to two standard deviations are shown in Fig. 3b. It was observed that similar values were measured at the different detector locations. This is consistent with the results from Monte Carlo simulations of the signal strengths.[11,12] In the figure it can be seen that Volunteer I exhibits a small signal on the right sinus ($L_{eq} \approx 10$ mm) while nothing was detectable on the left side. The setup presented has a detection limit of L_{eq} of about 2 mm, corresponding to an absorption fraction of $3 \cdot 10^{-5}$.[10] In contrast to the measurements performed on Volunteer I, a much larger signal was observed on Volunteer II in both the right ($L_{eq} \approx 26$ mm) and left sinus ($L_{eq} \approx 20$ mm). Clearly, a significant difference on the oxygen imprint could be observed between the volunteer with constantly recurring sinus problems and the volunteer with no history of such problems.

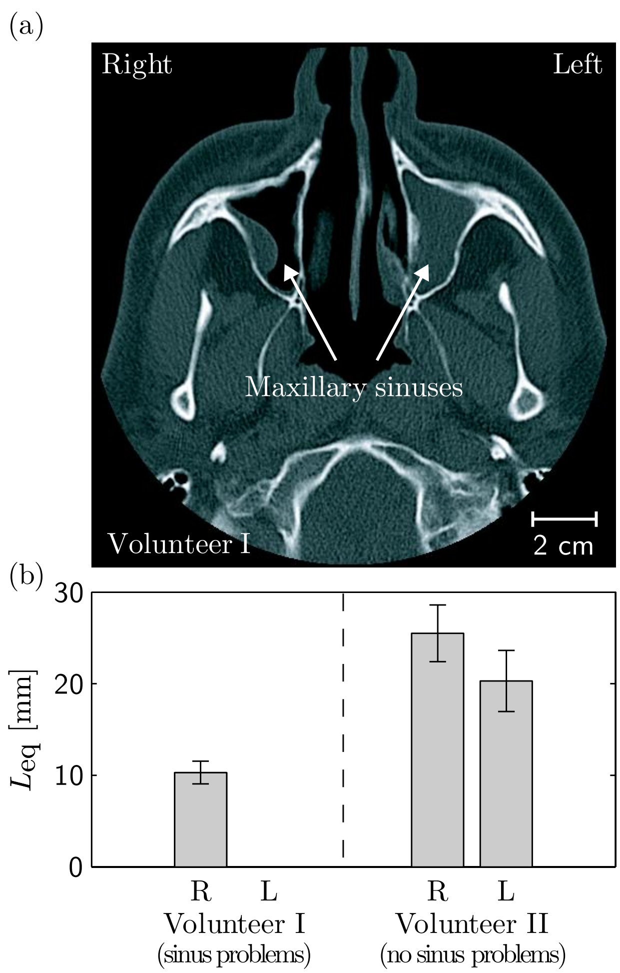

Figure 3. a) A CT image of Volunteer I with constantly recurring sinus problems. b) Signal levels study - Measured L_{eq} for both volunteers on the right and left maxillary sinus (Volunteer I with constantly recurring sinus problems, Volunteer II with no history of such problems).

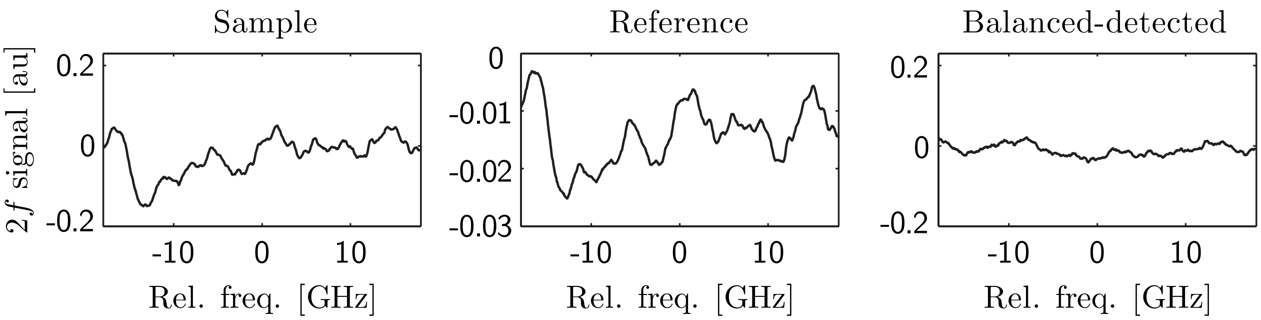

Figure 4. Control study - Typical recorded signals in this study from the sample detector (to the left) and the reference detector (center) when performing reference measurements. The fibre has been placed inside the mouth in contact with the cheek and the detector has been positioned on the opposite side of the cheek. The balanced-detection signal is also included. The remaining noise floor corresponds to about a L_{eq} of 2 mm (absorption fraction of $3 \cdot 10^{-5}$).

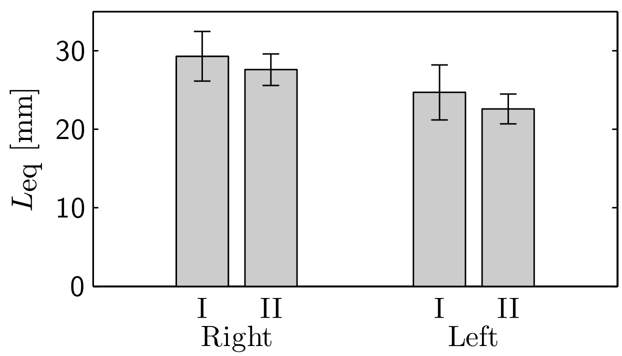

Figure 5. Reproducibility study - Average L_{eq} together with two standard deviations obtained from 10 measurements at each detector position (I : Cheek bone, II : Towards nose) and maxillary sinus for Volunteer II. The fibre and the detector were removed in between each recording.

Control

Before each measurement two reference measurements were performed. These measurements resulted in a consistently non-detectable signal providing the information that no oxygen offset is present in the setup. In our case a non-detectable signal corresponds to a L_{eq} of less than 2 mm as previously mentioned.[10] In Fig. 4 typical signals when performing reference measurements can be seen. From the balanced-detection signal the remaining noise floor can be observed.

Reproducibility

Fig. 5 shows the average L_{eq} together with error bars corresponding to two standard deviations obtained from 10 measurements at each detector position (I : Cheek bone, II : Towards nose) and maxillary sinus for Volunteer II when removing the detector and fibre between each recording. As can be seen, the standard deviation corresponds to about 10% for each position.

Gas exchange

Gas exchange studies were performed on both volunteers. No change could be observed in Volunteer I, while Volunteer II showed a decrease of signal when the nose cavity was flushed with pure nitrogen through a plastic tube positioned at the opening of the nostril. In Fig. 6 the invasion of N_2 in the right maxillary sinus of Volunteer II can be seen. The reinvasion of oxygen into the sinus can as well be observed when terminating the N_2 flush. During the measurements the fibre was placed on the palate, and the detector on the right cheek bone without

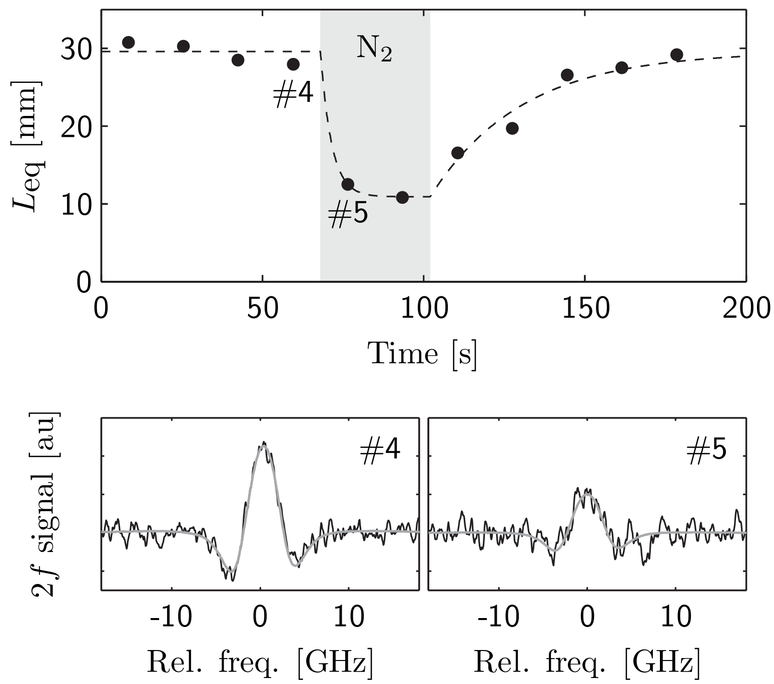

Figure 6. Gas exchange study - The measured L_{eq} (solid dots) together with a trend line (dashed line) in the right maxillary sinus of Volunteer II having no history of sinus problems. The oxygen level is first measured, N_2 is then flushed into the nasal cavity through the nostril and the invasion of the gas in the sinus is measured. The reinvasion of air is then recorded after terminating the N_2 flush. Two balanced-detection signals are also included in the figure; one before and one during N_2 flush.

being moved. Signals were averaged for about 15 s corresponding to the spacing between the measurement points. Two balanced-detection signals are also included in the figure; one signal before the gas is flushed and one during flushing. A reduction of about 2/3 was obtained in the signal for the case presented. More experiments with the same procedure have been performed showing different reductions depending on the N_2 flow.

4. CONCLUSION AND OUTLOOK

The technique described allows the monitoring of free oxygen gas in human sinuses, both in backscattering geometry, as demonstrated in Ref. [7] for the frontal sinuses, and in transmission geometry for the maxillary sinuses, as shown above. Actually, hybrids, where light is injected through the orbital wall close to the upper eye lid and the emerging light is detected against the forehead, or light is injected from the outside below the cheek bone and detected above the cheek bone have proved to be feasible, yielding strong signals, without the need of internal light injection.[13]

A person with sinus problems could readily be distinguished from a non-affected person also when varying scattering conditions were not accounted for. The degree of scattering, however, do not influence the data when the time constants for gas flow through the connecting channels are studied, since only the relative time variation of the signal is recorded. Like-wise, by forming a ratio between signals due to two gases interrogated at similar wavelengths, unknown scattering factors may be taken into account. Referencing around 935 nm to water vapor in the cavity, with its concentration determined only by the temperature (naturally thermostated to approximately 37^{o}C), it should be possible to directly determine the concentration of oxygen in the sinus, which might be related to the type of infection present.[13] Monitoring of free water vapor in scattering media was recently demonstrated in connection with wood drying.[14]

Based on the promising results reported here, a clinical study with well diagnosed patients, for which CT images are available, will be performed. This will be carried out together with an ear-nose-throat (ENT) clinic.

We anticipate, that a new and powerful non-intrusive optical method can be developed for assisting in fast and improved diagnostics of the common sinus problems, which frequently are abated with antibiotics, on sometimes uncertain grounds.

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