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Lars Kirsten*, Joseph Morgenstern, Mikael Timo Erkkilä, Martin Schindler, Jonas Golde, Julia Walther, Max Kemper, Thomas Stoppe, Matthias Bornitz, Marcus Neudert, Thomas Zahnert, and Edmund Koch

Functional and morphological imaging of the human tympanic membrane with endoscopic optical coherence tomography

Abstract: In this ex vivo feasibility study, endoscopic structural and functional optical coherence tomography (OCT) imaging with a field of view of 8 mm is presented allowing the inspection of nearly the entire tympanic membrane through the ear canal. The endoscope utilizes a gradient index optics for simultaneous OCT and video endoscopy. Additionally, Doppler-OCT allows the measurement of the tympanic membrane oscillation. Due to the fast image acquisition, only minor motion artifacts have been observed, which don't affect the image quality. In conclusion, endoscopic OCT is considered as a promising tool for the comprehensive examination of the human middle ear.

Keywords: Optical coherence tomography, Endoscopic imaging, Middle ear diagnostics.

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***Corresponding author: Lars Kirsten:** Technische Universität Dresden, Carl Gustav Carus Faculty of Medicine, Anesthesiology and Critical Care Medicine, Clinical Sensoring and Monitoring, Fetscherstraße 74, 01307 Dresden, Germany, e-mail: lars.kirsten@tu-dresden.de
Joseph Morgenstern, Max Kemper, Thomas Stoppe, Matthias Bornitz, Marcus Neudert, Thomas Zahnert: Technische Universität Dresden, Carl Gustav Carus Faculty of Medicine, Otorhinolaryngology, Fetscherstraße 74, 01307 Dresden, Germany, e-mails: joseph.morgenstern@uniklinikum-dresden.de, max.kemper@uniklinikum-dresden.de, thomas.stoppe@uniklinikum-dresden.de, matthias.bornitz@uniklinikum-dresden.de, marcus.neudert@uniklinikum-dresden.de, thomas.zahnert@uniklinikum-dresden.de
Mikael Timo Erkkilä, Martin Schindler, Jonas Golde, Julia Walther, Edmund Koch: Technische Universität Dresden, Carl Gustav Carus Faculty of Medicine, Anesthesiology and Critical Care Medicine, Clinical Sensoring and Monitoring, Fetscherstraße 74, 01307 Dresden, Germany, e-mails: mikael_timo.erkkilae@tu-dresden.de, martin.schindler1@tu-dresden.de, jonas.golde@tu-dresden.de, julia.walther@mailbox.tu-dresden.de, edmund.koch@tu-dresden.de
Julia Walther: Technische Universität Dresden, Carl Gustav Carus Faculty of Medicine, Anesthesiology and Critical Care Medicine, Medical Physics and Biomedical Engineering, Fetscherstraße 74, 01307 Dresden, Germany, e-mail: julia.walther@mailbox.tu-dresden.de
Mikael Timo Erkkilä: Medical University of Vienna, Center for Medical Physics and Biomedical Engineering, Waehringer Guertel 18-20, A-1090 Vienna, Austria, e-mail: mikael.erkkilae@meduniwien.ac.at

1 Introduction

In otological research, optical coherence tomography (OCT) is an emerging imaging technique for the non-invasive three-dimensional visualization of the tympanic membrane and the tympanic cavity behind with high spatial resolution in the range of 10 µm. OCT has been reported for the visualization of bacterial films behind the tympanic membrane [1] and for the visualization and assessment of effusions in the middle ear [2-3], which is important for the diagnosis of otitis media. Additionally, Doppler-OCT can be utilized for measuring the oscillation of the tympanic membrane during acoustical stimulation [4-5]. This can be useful for the indirect detection of effusions in the tympanic cavity by measuring the attenuated membrane oscillation. Since this high-resolution structural and functional imaging is a supplement to conventional diagnostics (otoscopy, ear microscopy, tympanometry), OCT is considered as a promising tool in future diagnostics.

Imaging the tympanic membrane through the human ear canal requires the adaption of OCT to a surgical microscope [6] or an ear speculum [3]. There, the field of view is limited to typically 3 mm due to the curved ear canal, which makes it difficult to image the entire tympanic membrane. Alternatively, endoscopic setups [7,8], e.g. by utilizing gradient index (GRIN) optics seems to be better suited, since they provide a fan-shaped scan pattern achieving a larger field of view.

In this ex vivo feasibility study, endoscopic structural and functional OCT imaging is presented allowing the inspection of nearly the entire tympanic membrane.

2 Materials and methods

2.1 Optical coherence tomography

The swept source OCT system has a center wavelength of 1300 nm, a spectral range of 120 nm and provides a sweep rate of 50 kHz. The OCT spectrum is sampled linear in wave number space by utilizing the clock signal of the swept laser source (Axsun Technologies). The depth profiles of reflectivity, referred to as A-scans, are calculated from the spectra measured, mainly by applying a Fourier transform.

For the inspection of the tympanic membrane in human temporal bones, a self-built endoscopic OCT probe was used. The endoscopic tube has an outer diameter of 4 mm and contains a GRIN optics of 2 mm diameter and optical fibers, which were connected to a cold light source for illumination. The GRIN optics is used for OCT imaging and simultaneous acquisition of video endoscopic images. The lateral and axial resolution for OCT was typically 50 µm and 10 µm (in tissue), respectively. The working distance (focus position) was adjusted to be 8 mm and the field of view was 8 mm as well. Each cross section consists of 512 A-scans and is acquired within 10 ms. The acquisition time for a volume scan (512 x 512 A-scans) is about 5.2 s.

In addition, the oscillation of the tympanic membrane was measured spatially resolved using a separate scan pattern [4] at a grid of 25 x 25 points, which covered the entire field of view. At each grid point, 512 consecutive A-scans have been acquired, which corresponds to 10 ms per grid point. The overall acquisition time for the functional measurement was 6.4 s. Simultaneously to the OCT measurement, the tympanic membrane was stimulated acoustically in the range between 500 Hz and 5 kHz with a chirp signal and the applied sound pressure was measured with a probe microphone. A phase-resolved Doppler analysis revealed the motion of the tympanic membrane. The transfer function, which was calculated via Fourier transform, gives the oscillation amplitude normalized to the sound pressure. Details on the measurement protocol have been published previously [4].

2.2 Experimental setup

In this study, freshly excised human temporal bones have been used. In order to simulate the future application, the cartilaginous part of the ear canal was kept as intact as possible. The temporal bone was adjusted with an articulated arm. The acoustical stimulation of the tympanic membrane was carried out with a loud speaker, which was placed at a distance of approximately 30 cm. A probe microphone was positioned at the entrance of the ear canal for measuring the applied sound pressure. After inserting the hand-held endoscope into the ear canal, a 3D structural volume scan and a function OCT scan was acquired. The tympanic membrane was accessible in 9 of 10 temporal bones. One specimen had a very narrow auditory canal being too small for the endoscopic tube.

3 Results and discussion

For visualizing the 3D structure of the tympanic membrane, a volume scan was acquired. Figure 1a-b shows the depth projection of the volume scan and the corresponding video endoscope image of a tympanic membrane in a left temporal bone. Nearly the entire tympanic membrane could be examined, except the superior part and the pars flaccida. In Figure 1b, the manubrium of malleus is visible between the middle and the upper left in the image.

The Doppler-OCT measurement revealed the oscillation of the tympanic membrane, which can be calculated in post-

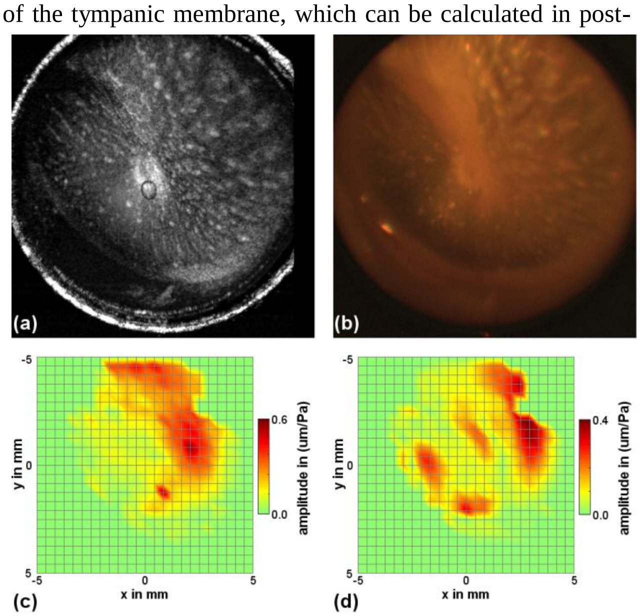

Figure 1: Imaging results showing (a) the depth projection of the OCT volume scan, (b) the corresponding video endoscope image and (c, d) the oscillation amplitude maps for 1092 Hz (c) and 3034 Hz (d), which have been calculated from the functional Doppler-OCT scan.

processing for frequencies within the range of 500 Hz to 5 kHz. Exemplary oscillation maps are depicted in Figure 1c-d. At the resonance of the tympanic membrane (Figure 1c), the oscillation amplitude exhibits a maximum in the posterior quadrants and is small at the manubrium of malleus and in the anterosuperior quadrant. In case of higher oscillation frequencies, e.g. at 3 kHz (Figure 1d), the maximum oscillation amplitude is decreased and multiple maxima are visible in the oscillation map. For calculating the oscillation maps, a mask was applied, which sets the oscillation amplitude to zero for grid points, where the evaluation failed, e.g. in case of small signal intensity.

Due to the fast image acquisition, only minor motion artifacts are observed in the images. Single cross sections and M-scans of the functional Doppler measurement are not affected by motion artifacts, since the acquisition time was only 10 ms. Only a few slight misalignments between consecutive cross sections are visible in the entire volume scan.

4 Conclusion

OCT is considered as a promising tool for the comprehensive examination of the human middle ear, because it allows three-dimensional high-resolution imaging of the tympanic membrane and the spatially resolved measurement of the tympanic membrane oscillation. The endoscope provided a field of view of 8 mm at an appropriate working distance, which has proven to be suitable for imaging a large part of the entire tympanic membrane. In the 3D volume scan, only minor motion artifacts occurred due to the hand-held OCT probe, whereas no motion artifacts have been observed in single cross sections and Doppler evaluation.

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