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Imaging the tympanic membrane oscillation *ex vivo* with Doppler optical coherence tomography during simulated Eustachian catarrh

Lars Kirsten*[a], Anke Burkhardt[a], Jonas Golde[a], Julia Walther[a,b], Thomas Stoppe[c], Matthias Bornitz[c], Max Kemper[c], Thomas Zahnert[c], Edmund Koch[a]
[a]Technische Universität Dresden, Faculty of Medicine Carl Gustav Carus, Department of Anesthesiology and Intensive Care Medicine, Clinical Sensoring and Monitoring, Fetscherstraße 74, 01307 Dresden, Germany
[b]Technische Universität Dresden, Faculty of Medicine Carl Gustav Carus, Medical Physics and Biomedical Engineering, Fetscherstraße 74, 01307 Dresden, Germany
[c]Technische Universität Dresden, Faculty of Medicine Carl Gustav Carus, Clinic of Otorhinolaryngology, Fetscherstraße 74, 01307 Dresden, Germany

ABSTRACT

Recently, optical coherence tomography (OCT) was utilized in multiple studies for structural and functional imaging of the middle ear and the tympanic membrane. Since Doppler OCT allows both, the spatially resolved measurement of the tympanic membrane oscillation and high-resolution imaging, it is regarded as a promising tool for future *in vivo* applications. In this study, Doppler OCT is utilized for the visualization of the tympanic membrane oscillation in temporal bones with simulated Eustachian catarrh, which was realized by generating a depression in the tympanic cavity. The transfer function, meaning the oscillation amplitude normalized to the applied sound pressure, is measured frequency resolved in the range from 0.5 kHz to 6 kHz and with a lateral spatial resolution of 0.4 mm. Typical oscillation patterns could be observed in case of ambient pressure in the tympanic cavity. Under depression the characteristic oscillation patterns were observed with widely congruent appearance but at higher frequencies.

Keywords: optical coherence tomography, Doppler, middle ear, tympanic membrane oscillation

1. INTRODUCTION

Diseases of the middle ear are often accompanied by changes of the tympanic membrane morphology and tympanic membrane function. However, the established diagnostics, namely otoscopic techniques, tympanometry, audiometry and laser Doppler vibrometry, provide only limited information about the tympanic membrane structure and about the tympanic membrane function. With these techniques it is not possible to visualize the tympanic membrane resolved in depth, to visualize the tympanic cavity behind the tympanic membrane and to measure the oscillation of the tympanic membrane spatially resolved *in vivo*.

This diagnostic gap could be closed using optical coherence tomography (OCT). OCT is a noninvasive and contact-free interferometric imaging technique for high-resolution visualization of tissue. Main applications can be found in medicine and biomedical research. OCT utilizes an interferometer setup and broadband near infrared light sources. The light, which is reflected or backscattered from the sample, is superimposed with reference light. In Fourier Domain OCT, the spectrum of the interfering light is measured. A depth profile of the sample reflectivity (A-scan) can be calculated by applying mainly a Fourier transform to the interference spectrum. Cross-sections (B-scans) and volume scans consist of several A-scans, which are acquired during a transverse beam deflection.

OCT is also a promising tool for investigating the structure and function of the tympanic membrane and the middle ear as demonstrated by various authors in the last years. Since OCT can resolve the tissue structure in three dimensions with high spatial resolution of approximately 10 µm or better, it can be utilized for visualizing and investigating the middle ear morphology *in vivo* [1, 2], as it is not possible with conventional diagnostics.

*lars.kirsten@tu-dresden.de; phone +49 351 458 6133; fax +49 351 458 6325; www.tu-dresden.de/medksm

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Furthermore, phase-resolved Doppler OCT can be used for the quantification of the tympanic membrane oscillation as demonstrated using animal models [3] as well as for human tympanic membranes *ex vivo* [4, 5]. Compared to holographic imaging [6] and laser Doppler vibrometry [7], Doppler OCT could be easily applied in future *in vivo* measurements and OCT can be used for combined structural and functional imaging of the entire tympanic membrane. Recently, an OCT measurement strategy allowed the determination of the tympanic membrane oscillation over a wide frequency range in a very short measurement time of about 5 s [5].

The potential of OCT is the diagnosis of inflammatory and degenerative changes of the middle ear, e. g. otitis media. The typical pathogenesis of otitis media starts with an Eustachian catarrh resulting in a depression in the tympanic cavity, compared to the ambient pressure being normally present in the tympanic cavity. In this *ex vivo* study, it is demonstrated that Doppler OCT can be used to detect variations in the oscillation patterns of the tympanic membrane, which are correlated to a depression in the tympanic cavity.

2. METHODS

For Doppler-OCT, a swept-source OCT system operating at 1300 nm center wavelength and providing 60 kHz A-scan rate was utilized. The axial resolution is 13.5 µm in air and the lateral resolution is 11.5 µm. Details on the OCT system have been currently published in [5].

For this *ex vivo* study human temporal bones were used. The specimen was proven to be free of pathological alterations by an ENT medical inspection. The ear canal was removed in order to provide sufficient access for the OCT scanner head. The simulation of an Eustachian catarrh was carried out by producing a depression in the tympanic cavity (with reference to the ambient pressure). For that purpose, a syringe was connected to the tympanic cavity via the Eustachian tube. The adjusted pressure difference was measured using a pressure transducer.

The oscillation of the tympanic membrane was measured on a grid of 25 x 25 points in analogy to [5]. At each grid point, a M-scan (B-scan at fixed lateral position) composed of 512 A-scans was acquired, while the tympanic membrane was acoustically stimulated with a loudspeaker using a chirp signal. This chirp covered the frequency range of 0.5 kHz to 6 kHz, which is the relevant range for speech perception and is of high interest for future diagnostic applications. The applied sound pressure was measured next to the tympanic membrane with a probe microphone. A phase-resolved Doppler evaluation of the M-scan revealed the axial velocity component (velocity component in beam direction), and thus the oscillation amplitude.

The frequency response A of the oscillation amplitude and the frequency response of the sound pressure R (reference signal) are calculated mainly by applying a Fourier transform to the time series of the Doppler phase difference or sound pressure, respectively. The transfer function $T=A/R$ providing the normalized oscillation amplitude (oscillation amplitude per sound pressure amplitude) is used for the evaluation of the tympanic membrane oscillation. The transfer function is mostly insensitive to imperfections in the acoustic excitation spectrum. The frequency resolution, which is 133 Hz for the presented results, is the frequency increment after the Fourier transform and is given by the duration of the analyzed part of the M-scans.

The measurement time for the entire grid is only 5.3 s making the method promising for future *in vivo* applications. It is possible to evaluate single transfer functions for individual points as well as to visualize the oscillation pattern of the entire tympanic membrane for frequencies in the range between 0.5 kHz and 6 kHz. The map of the oscillation pattern for the entire tympanic membrane was calculated by assuming a sinusoidal oscillation for each grid point with amplitude and phase extracted out of the transfer functions.

3. RESULTS AND DISCUSSION

The structure of the tympanic membrane was visualized with a three-dimensional scan, which is shown in figure 1. The tympanic membrane under investigation has a diameter of approximately 10 mm and the thickness of the membrane is between 150 µm and 300 µm.

The functional OCT measurement reveals the oscillation of the tympanic membrane. Figure 2 shows characteristic oscillation patterns for ambient pressure in the tympanic cavity and for a depression. In figure 2a-c, depth projections of the corresponding 3D scans are shown for comparison. The red line indicates the position of the manubrium of malleus.

In the normal case of ambient pressure (left column), the typical oscillation patterns could be observed. The resonance of the tympanic membrane was measured at 1.3 kHz. At this frequency, the pars tensa, which is the three-layered main membrane of the tympanic membrane, is oscillating in phase and the oscillation amplitude has its maximum. More complex oscillation patterns are observed at higher frequencies, for example an out-of-phase oscillation of the anterior and posterior part of the tympanic membrane at 2.3 kHz and a circular arrangement of oscillation maxima at 3.5 kHz. These findings about the oscillation patterns are consistent to previously reported measurements with OCT [5] and holographic imaging techniques [6, 8].

Due to a depression in the tympanic cavity, the tympanic membrane is pulled a small distance into the tympanic cavity. This displacement amounts approximately 300 µm at the umbo for a depression of 200 mmH_2O. The increased membrane tension should influence the transfer function and the oscillation patterns. This could be actually observed with the functional OCT measurement. In figure 2, the oscillation patterns for a depression of 100 mmH_2O and 200 mmH_2O are shown in the middle and right column, respectively. The oscillation maps represent the oscillation patterns already observed for ambient pressure. But, the frequencies, where the patterns occur in case of depression, are higher. For example, the resonance frequency for the in-phase oscillation is shifted from 1.3 kHz to 1.6 kHz in case of 100 mmH_2O depression and to 1.9 kHz for 200 mmH_2O depression. Comparable frequency shifts are also observed for the other oscillation patterns presented. A decrease in amplitude was observed mainly for the first resonance (1.3 kHz), whereas the amplitude of the higher order oscillation modes remained nearly constant.

The comparison of the transfer functions is shown for individual grid points, for the umbo and for a point on the anterior part of the tympanic membrane, in figure 3. For the umbo, the resonance peak with oscillation amplitude of 0.1 µm/Pa is clearly visible at ambient pressure. Over the frequency range investigated, the oscillation amplitude is decreasing by one order of magnitude. In case of depression, the resonance peak is shifted towards higher frequencies, which is consistent with the shift observed evaluating the oscillation patterns. The amplitude at the resonance peak is slightly decreasing for the adjusted depression.

A more complex transfer function can be observed for points on the anterior segment, as exemplarily shown in figure 3b. In addition to the resonance peak at 1.3 kHz, the transfer function exhibits a further peak or increase in amplitude above 3 kHz. In case of the depression, the transfer function is shifted to higher frequencies, which is visible for the first resonance and for the second maximum as well. The frequency shift is indicated by three arrows at characteristic positions of the transfer function.

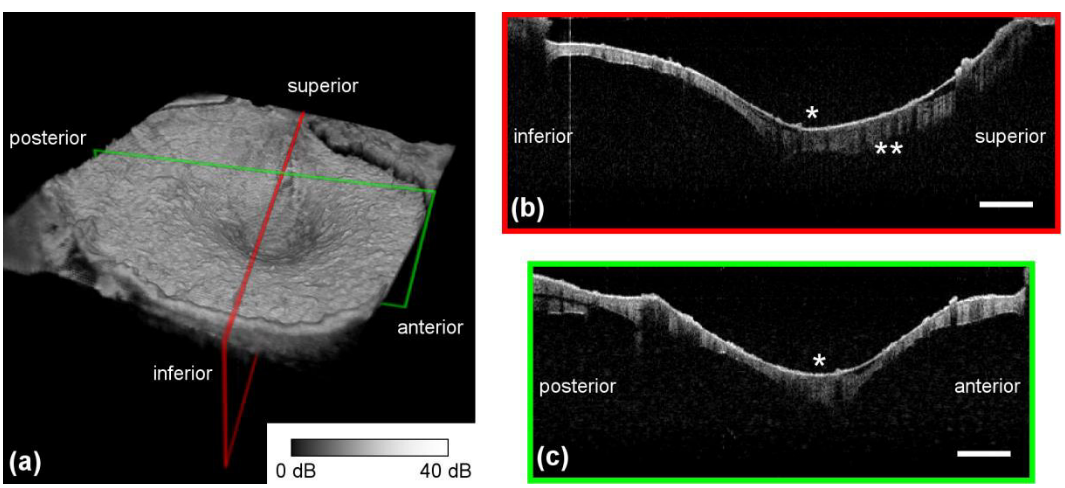

Figure 1. (a) 3D OCT image of the human tympanic membrane investigated. (b) OCT cross-section at the red marked position through the umbo (*) and along the manubrium of malleus (**). (c) Perpendicular cross-section at the green marked position. Scale bars correspond to 1 mm.

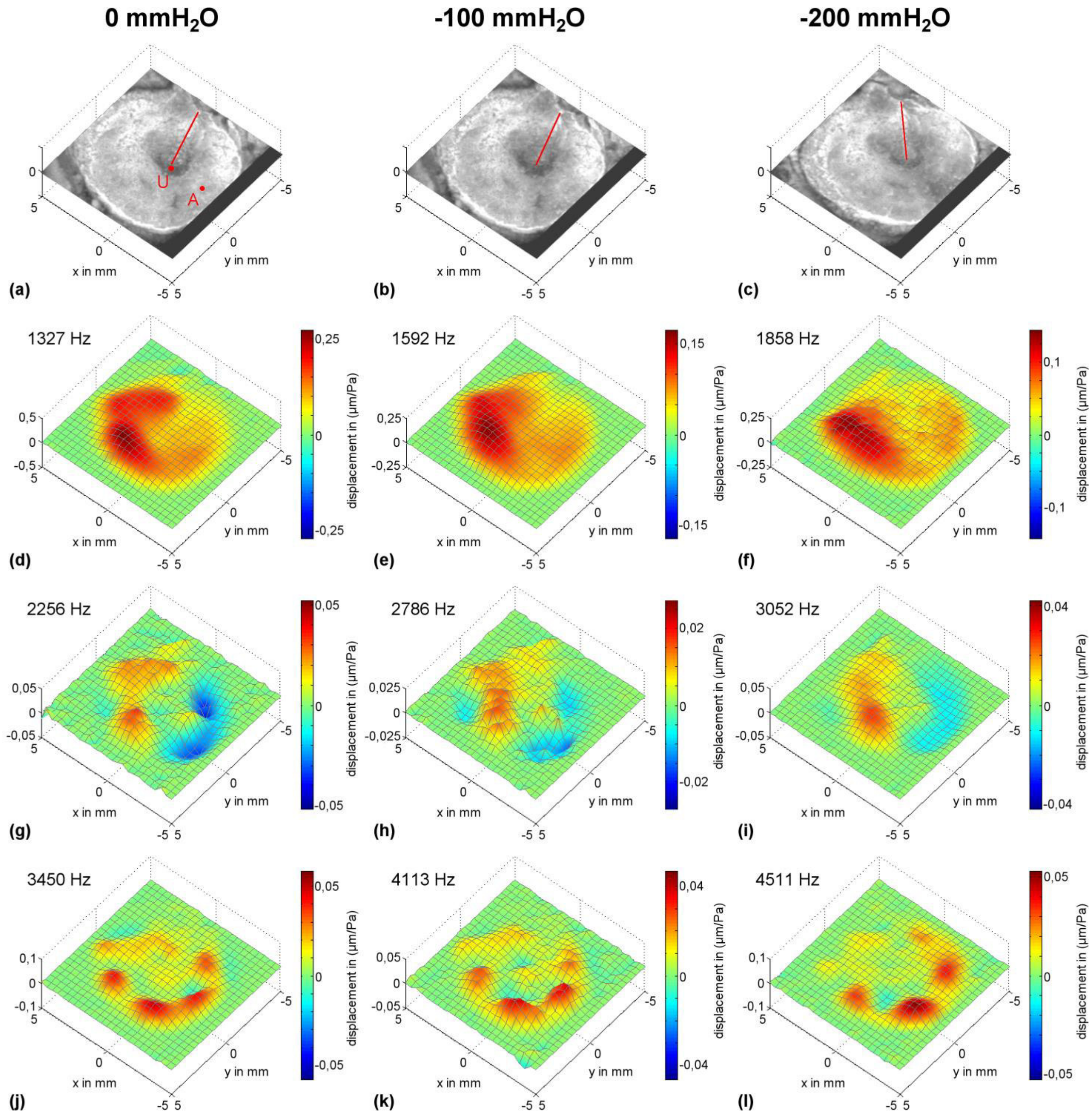

Figure 2. Oscillation patterns of a human tympanic membrane *ex vivo* measured with Doppler-OCT. The deflection maps show different oscillation patterns: the resonance of the tympanic membrane with in-phase oscillation of the pars tensa (d-f), an out-of-phase oscillation of the anterior and posterior part of the pars tensa (g-i) and a circular arrangement of amplitude maxima (j-l). The patterns are shown for ambient pressure (0 mmH_2O depression) in the tympanic cavity (left column), for a depression of 100 mmH_2O (middle column) in the tympanic cavity and for a depression of 200 mmH_2O (right column). The depth-projection images (a-c) show the position of the tympanic membrane and the position the manubrium of malleus (red line) for comparison. In fig. 3, transfer functions are evaluated for the umbo (U) and for a point on the anterior part of the membrane (A), which is indicated in (a).

The evaluation of the spatially resolved oscillation patterns and the evaluation of single transfer functions reveal the effect of depression in the tympanic cavity on the tympanic membrane oscillation. However, the spatially resolved oscillation measurement allows the assessment of typical oscillation patterns. Analyzing single transfer functions without the knowledge of the overall membrane oscillation might be challenging because the transfer function depends on the selected position on the tympanic membrane. Only the resonance peak can be clearly identified, whereas the observed oscillation patterns seem to have mostly no direct correspondence in the transfer function, which could be identified. Thus, the spatially resolved oscillation measurement is a more reliable way to analyze the tympanic membrane function.

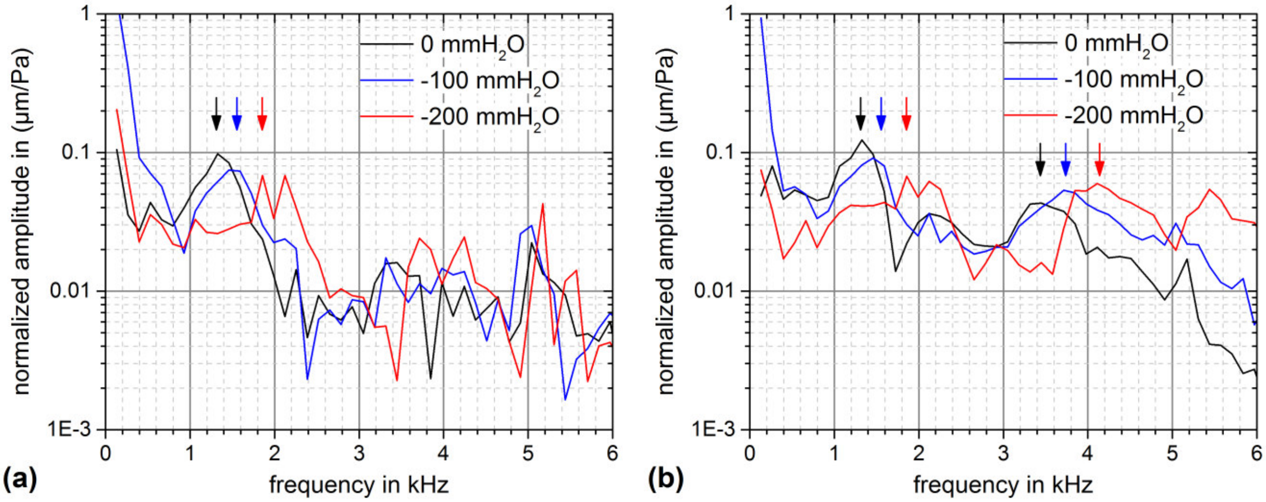

Figure 3. The amplitude of the transfer function is shown for the umbo (a) and for a point on the anterior part of the pars tensa (b), in each case for ambient pressure in the tympanic cavity (0 mmH2O) and for a depression of 100 mmH_2O and 200 mmH_2O in the tympanic cavity. The positions on the tympanic membrane are marked in fig. 2a.

4. CONCLUSION

Doppler OCT allows the measurement of the tympanic membrane oscillation with high frequency resolution and with high spatial resolution. It could be shown that the changed oscillation of the tympanic membrane during depression in the tympanic cavity can be investigated with Doppler OCT imaging. Under depression, the oscillation patterns recurred at higher frequencies maintaining their appearance. A decrease of the oscillation amplitude could be observed for the resonance at 1.3 kHz but not for higher order oscillation patterns. The evaluation of the spatially resolved oscillation patterns, i. e. the evaluation of the deflection maps, allows a reliable assessment compared to the interpretation of single transfer functions. Functional OCT imaging is a promising technique for an alternative diagnostics at the middle ear. The presented study suggests that OCT could be utilized for the diagnosis of an Eustachian catarrh.

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