The Measurement System for Experimental Investigation of Middle Ear Mechanics

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Abstract. *This paper presents a measurement system for non-contact measurements of vibration parameters of the structural elements of the organ of hearing. It proposes an original methodology of in-vitro measurements of the human ear, round window membrane motions. It was found that the Scanning Laser Doppler Vibrometry (LDV) technique is a useful research tool in micro- and nanometer scales, not only for technical, but also for biological objects.*

Keywords: laser Doppler vibrometry, middle ear mechanics, round window membrane

1. Introduction

The human middle ear is a complex mechanical system, which transmits sound from the external ear canal to the inner ear structures. The ossicular chain is the most important part of that system. The physiological range of the middle ear structural elements displacement amplitudes in the process of sound conduction does not exceed 100 nm. Both, diagnosis of the hearing organ in its physiological condition, and the hearing organ after ossicular chain reconstruction, require measuring equipment which enables non-contact measurements of vibration parameters in very low amplitudes and in a wide range of acoustic frequencies. Laser Doppler Vibrometry (LDV), especially scanning one, is a modern measurement method which meets such requirements.

The objective of this study is experimental verification of the applicability of the LDV method in non-contact, human ear, round window (RW) membrane vibration measurements, in specimens in their physiological condition, pathological condition and post-implantation of various kinds of ossicular chain prosthesis. The measurement results can be used to model the process of sound transmission [1], to test middle ear prostheses [2,3], to diagnose of pathologies [4,5] and for intraoperative control of otosurgery effectiveness [6]. Despite significant advances in this field, the relation between the sound transmission process and the structure of hearing organ remains under-researched. Therefore, it is purposeful to expand on this topic in research works of both, an experimental, as well as theoretical and model nature. Developing LDV-based diagnostic equipment and introducing it into otorhinolaryngological practice is of great necessity.

2. Subject and Methods

Our research was conducted in-vitro with the use of appropriately prepared fresh human temporal bone specimens obtained postmortem. The experiments consisted of measuring the amplitude and phase of RW membrane motions depending on the sound frequency (400 Hz – 10 kHz) with the sound pressure entering the external auditory canal at 90 dB. The amplitude and phase functions of velocity transmission were defined according to the experimental results, depending on the ossicular chain state. The course of the destignated functions can differentiate middle ear pathologies and can be used to optimize the construction of auditory prostheses.

Preparing the specimen

Literature sources [7,8] show, that the functioning of middle ear structures in fresh cadaver temporal bones is the same as their functioning in physiological condition. Our procedure of preparing the physiological specimen required the following steps to be taken: (1) harvesting a segment of the temporal bone within 48 hours after death, (2) microscopic inspection of the specimen, (3) reaming until the tympanic membrane was fully exposed (the bony rim around the tympanic annulus was left intact), (4) conducting a wide posterior tympanotomy (sometimes sacrificing part of the facial nerve canal with the facial nerve) and making the round window and stapes visible, (5) gluing a foam earmold onto the remaining bony rim, (6) placing the microphone tube (approx. 2 mm away from the tympanic membrane) and a ER3-04 loudspeaker adapter (approx. 4-5 mm away) in the earmold, (7) periodically dipping the specimen in a saline solution to maintain the proper hydration of the structure.

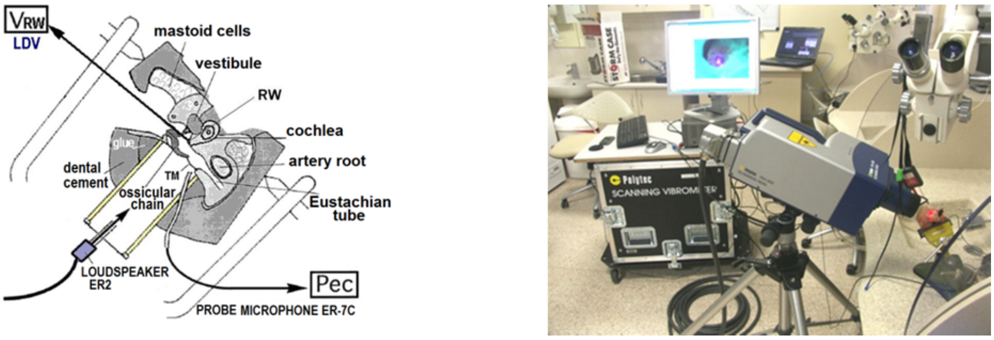
Acoustic system

The acoustic signal introduced into the substitute external auditory canal of the temporal bone specimen induces the tympanic membrane vibrations, and causes vibration of the ossicular chain. A sound is produced by a probe loudspeaker connected to an adapter placed into the external auditory canal. In our study an input sound signal generated by a computer system (VIBSOFT, Polytec PI) and amplified by an acoustic amplifier (Revox A78) was supplied to the earmold placed into the specimen. The procedure of acoustic stimulation involves: (1) calibrating the VIBSOFT system, the loudspeaker and probe microphone, (2) selecting and setting the sound level intensity of the stimulating signal (90dB SPL), (3) selecting and setting the frequency of the input signal (sounds with a center frequency of successive one-third octave bands were transmitted into the external auditory canal), (4) transmitting sounds into the external auditory canal with the aid of a loudspeaker (ER-2, Etymotic Research) attached to an adapter (ER3-04, Etymotic Research) placed into the earmold, (5) controlling the sound intensity level of the stimulating sound with a probe microphone (ER-7C, Etymotic Research) placed in the microphone tube approx. 2 mm away from the tympanic membrane (TM).

Opitical system

The optical measurement system was created from a commercially available SLDV PSV 400 scanning laser Doppler vibrometer produced by Polytec GmbH, Waldbronn, Germany. The vibrometer in use is characterized by the following parameters: scanning surface of 512 by 512 measuring points, scanning laser head equipped with a type He-Ne 633 nm laser of < 1 mW power, vibrometer sensor (OFV-505), scanning unit (OFV 040) featuring a +/- 20° scanning range and < 0,002° resolution, and a VTC 24 video camera featuring Auto Focus and a 72x zoom, vibrometer controller (OFV-5000) equipped with a RS-232 port, which enables measuring velocity in the 0,01 µm/s – 10 m/s range for frequencies in the 0 MHz – 1 MHz range, a PSV E 400 interface for connecting the measuring head and vibrometer controller with the measurement data compiling system, measurement data compiling system, comprised of a PC computer with software and a generator of low-intensity signals.

Figure 1 shows the scheme of the experiments (measurements of the parameters of the round window membrane motions in a physiological specimen in the frequency function) and a partial view of the measurement system.

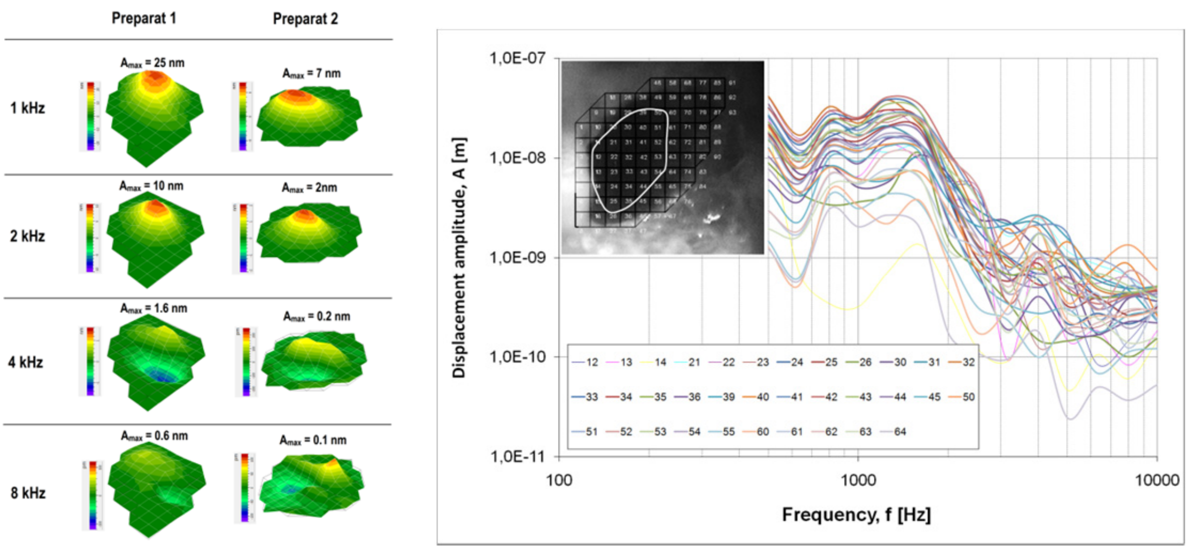


(a) (b)

Fig. 1. (a) Scheme of the experimental measurements (Stage 1), (b) View of the measurement system.

3. Results

The original research comprised of measuring parameters of the human ear round window membrane vibrations. The scanning LDV method was used to measure the following vibration parameters of 34 targets on the round window membrane in frequency function of the acoustic input signal: (1) displacement amplitude, (2) velocity amplitude and (3) phase displacement, where the determined characteristic parameter was the sound pressure level of the input signal of 90 dB SPL. The amplitude-frequency characteristics for targets located on the surface of the RW membrane are shown in Figure 2. The characteristics of the RW membrane vibrations were determined based on measurements of displacement in the grid nodes when the sound pressure is 90 dB SPL and frequencies ranging from 400 Hz up to 10 kHz in the external auditory canal.



(a) (b)

Fig. 2. (a) The vibration pattern of the RW membrane at 1, 2, 4 and 8 kHz, (b) Magnitude of the displacement amplitude of 34 measurement targets on the RW membrane.
The result is from specimens in physiological state stimulated with an AC when the sound pressure level is 90 dB SPL in the external auditory canal.

In both physiological specimens, the Preparat 1 and Preparat 2 at 1 and 2 kHz vibration frequencies all measurement targets oscillate in the same phase, yet a difference in the location of points characterized by the greatest displacement amplitude values located on the RW membrane is noticeable (Fig.2a). The displacement amplitude for all measurement points in the low-frequency range (0.5–2 kHz) is 10-15 times greater than in the high frequency range (2–10 kHz). Characteristic resonant frequencies of the middle ear are noticeable.

4. Discussion

The measurement results for the human ear RW membrane vibrations in two fresh cadaver temporal bone specimens for air conduction at 90 dB SPL in the external auditory canal showed that the maximum displacement amplitude in the central area of the RW membrane is different in both specimens. This difference of the maximum vibration amplitude was related to different shapes and sizes of the RW membrane in each specimen, which is a characteristic trait of biological objects demonstrating individual variability. The decrease in the displacement amplitude of vibrations for frequencies above 2 kHz is related to different vibration phases in each measurement point on the RW membrane The circumferential ring pattern of displacement maxima in Fig.2 is consistent with the presence of standing waves on the RW surface at frequencies below 2kHz. Based on a detailed iso-amplitude chart analysis it was found that the vibrations of measurement points spread across the entire surface of the RW membrane for all examined specimens in low-frequency ranges were single-phase vibrations. Above 1250 Hz – 2000 Hz frequencies, the phase of vibration for points placed in various parts of the RW membrane was different. When examining the iso-phase contours, indications of both modal and traveling waves can be seen. 3D visualization shows that modal vibration was dominating at the low frequencies and travelig wave motion at the high frequencies.

The motion of the RW membrane can be used to measure the cochlear stimulation for the evaluation of middle ear ossicle reconstruction. Therefore one can assume that as a result of conducting a standard implanting procedure, a significant change in biomechanical parameters of the middle ear conductive apparatus takes place, which causes a significant change in the input impedance of the cochlea and a significant decrease in perilymph stimulation levels. The result of a decrease in stimulation of the perilymph in the post-implantation condition, in comparison with its physiological condition, in case of otologic surgery conducted in-vivo, could be the incomplete closure of the air-bone gap resulting in hearing outcomes showing signs of conductive hearing loss.

5. Conclusions

The LDV method is a useful research tool in micro- and nanometer scales. The latest scanning systems enable taking measurements of vibrations in the picometer amplitude range and can be used not only to examine technical but also biological objects. The presented experimental method of measuring vibration parameters of structural elements of the middle ear can be applied to: (1) research aiming to explore the phenomenon of conducting sound through physiological, pathological and reconstructed structures of the middle ear, (2) verifying computer- modeling and simulating procedures of sound conduction by the structures of the middle ear and examining the influence of various parameters on the effectiveness of stimulation of the perilymph in the cochlea of the inner ear, (3) aiding the process of constructing various kinds of middle ear prosthetics (including optimizing the build and methods of implantation) by experimental research on prototypes of such prostheses, (4) in-vivo diagnostics whose purpose is to differentiate pathological conditions (tympanosclerosis, otosclerosis, ossicular chain disruption, diagnosing the inner ear by measurement of acoustic otoemissions) and predicting results of hearing improvements achieved after otological procedures, (5) supporting the process of surgery (intraoperative diagnostics).

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References

[1] Gan R, Reeves B, Wang X. Modeling of Sound Transmission from Ear Canal to Cochlea. *Annals of Biomedical Engineering*, 35 (12): 2180-2195, 2007.

[2] Chien W, Rosowski R, Merchant S. Investigation of the Mechanics of Type III Stapes Columella Tympanoplasty Using Laser-Doppler Vibrometry. *Otol Neurotol*, 28 (6): 782-787, 2007.

[3] Puria S, Kunda L, Roberson J Jr, Perkins R. Malleus-to-footplate ossicular reconstruction prosthesis positioning: cochleovestibular pressure optimization. *Otol Neurotol*, 26 (3): 368-379, 2005.

[4] Huber A, Schwab C, Linder T, Stoeckli S, Ferrazzini M, Dillier N, Fisch U. Evaluation of Eardrum Laser Doppler Interferometry as a Diagnostic Tool. *The Laryngoscope*, 111: 501-507, 2001.

[5] Nakajima H, Ravicz M, Rosowski J, Peake W, Merchant S. Experimental and clinical studies of malleus fixation. *The Laryngoscope*, 115 (1): 147-154, 2005.

[6] Huber A, Linder T, Ferrazzini M, Schmid S, Dillier N, Stoeckli S, Fisch U. Intraoperative assessment of stapes movement. *Ann Otol Rhinol Laryngol*, 110 (1): 31-35, 2001.

[7] Rosowski J, Davis P, Merchant S, Donahue K, Coltrera M. Cadaver Middle Ears as Models for Living Ears: Comparison of Middle Ear Input Immitance. *Ann Otol Rhinol Laryngol*, 99: 403-412, 1990.

[8] Goode R, Ball G, Nishihara S. Measurement of umbo vibration in human subjects - method and possible clinical applications. *Am J Otol*, 14: 247-251, 1993.