Round Window Membrane Vibration Measured by Laser Doppler Vibrometer

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Abstract. *The paper describes the results of non-contact measurements of the human ear round window (RW) membrane vibration parameters using the scanning Laser Doppler Vibrometer (LDV) in freshly harvested human cadaver temporal bone specimens – a procedure conducted for the first time in Poland. A PSV 400 Scanning Laser Vibrometer system (Polytec, Waldbronn, Germany) was used in the research. The paper presents amplitude-frequency and phase-frequency characteristics of the RW membrane vibrations in an anatomically correct specimen (in its physiological conditions) and in the same specimen after teflon piston stapes prosthesis implantation. The characteristics were measured in a 400Hz – 10000Hz frequency range with a 90 dB sound pressure level applied to the external auditory canal. It was indicated that measurements of the round window membrane vibrations may be a tool for evaluating hearing results of surgical ossicular chain reconstruction, especially in case of otosclerosis surgery.*

Keywords: Round Window, Vibration, Laser Doppler Vibrometry, Mechanics of Hearing Organ

1. Introduction

The process of conducting sound waves from the external auditory canal to the structures of the inner ear is a complex mechanical process, in which air conduction (AC) plays the determining role. In the AC process the sound waves entering the auricula are directed through the external auditory canal and contact the surface of the tympanic membrane causing it to vibrate. That vibrations are passed on through the ossicular chain (maleus, incus and stapes). The vibrating stapes footplate located in the oval window (OW) niche of the bony cochlea and attached by the annual ligament cause perilymph, filling the inner ear, to vibrate. Because the perilymph is incompressible, fluctuations of the stapes cause the round window membrane interaction.

It is assumed that the amplitude of the vibrations of the stapes and the volume of the vibrating fluid neighboring the OW are a measure of the input impedance of the cochlea [1-3]. It has been empirically shown, that for frequencies bellow 2000 Hz the volume of the vibrating fluid neighboring the OW is the same as next to the RW, where the vibrations take place in anti-phase [4,5]. Hence, in order to determine the degree of stimulation of the cochlea in a low-frequency range (up to 2000 Hz), the volume of the vibrating fluid by the RW or the vibration amplitude of the RW membrane can be used. This is especially crucial in a situation in which the real stimulation of the cochlea is difficult to predict, e.g., after implanting various types of prostheses which transmit vibration energy to the cochlea instead of the immobilized stapes footplate (stapedotomy or stapedectomy procedures). In case the manner of cochlea stimulation changes, the aforementioned stimulation can be examined by measuring the vibrations of the RW membrane maintained in physiological condition.

2. Subject and Methods

The research was conducted in-vitro with the use of appropriately prepared fresh human temporal bone specimens obtained postmortem. Source literature [6,7] reveals, that the functioning of auditory structures in a short time postmortem specimens is the same as their functioning in physiological condition, providing that the following three requirements are met: (i) the temporal bone specimens are harvested from human cadavers within 48 hours after death, (ii) specimens are secured against drying and stored without being frozen in a temperature of approx. 5°C, until the time of measurements, (iii) the measurements are taken in a 1 to 6 day period after death. The research was conducted at the ICHS Physiology and Pathology of Hearing Institute in Kajetany, Poland and consisted of measuring the amplitude and phase of RW membrane vibrations in a frequency function (400 Hz – 10 kHz) with the sound pressure entering into the external auditory meatus at 90 dB. The amplitude-frequency and the phase-frequency characteristics were defined according to the experimental results, depending on the ossicular chain state. The measuring system was assembled on the basis of a commercially available SLDV PSV 400 scanning laser vibrometer produced by Polytec GmbH, Waldbronn, Germany. A detailed description of the measuring system as well as its parameters is supplied in "The Measurement System for Experimental Investigation of Middle Ear Mechanics" [in this Proceedings] and the view of part of the test stand is shown in Figure 1(a).

In order to prevent individual physiological differences among individual specimens from having impact on the results, the experiment was conducted in two stages: (1) stage I – measurements taken in a physiological specimen (the ossicular chain and tympanic membrane were left intact, the middle and inner ear structures were properly hydrated and the tympanic cavity properly ventilated), (2) stage II – vibration measurements in the same specimen after implanting a stapes prosthesis (retail 0.47-mm-diameter Teflon piston stapes prosthesis was used, fastened appropriately to the long crus of the incus by a platinum ribbon).

3. Results

Results of original empirical research into the parameters of the human ear round window (RW) membrane vibration in four physiologically fresh temporal bone specimens, conducted in accordance with the laser Doppler vibrometry method were obtained for air conduction at a calibrated sound intensity level of 90 dB and with frequencies ranging from 400 Hz up to 10 kHz in the external auditory canal. The characteristics of the RW membrane vibrations were determined based on measurements of displacement in measurement grid nodes. The amplitude-frequency characteristics of specimen Preparat 1 before and after stapes prosthesis implantation for targets located on the surface of the RW membrane are shown on Figure 1.

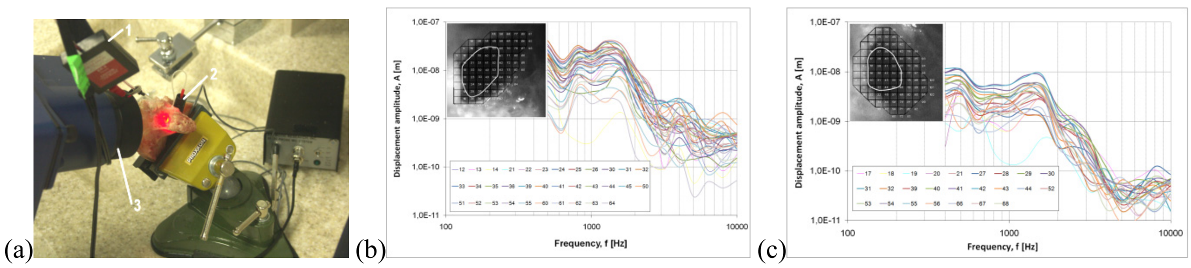

Fig. 1. (a) Photo of part of the test stand. 1 – loudspeaker ER2, 2 – probe microphone ER-7C, 3 – scanning laser head OFV-505 , (b) Magnitude of the displacement amplitude of 34 measurement points on the RW membrane – stage I (physiological), (c) Magnitude of the displacement amplitude of 25 measurement points on the RW membrane – stage II (implanted). The result are from specimen Preparat 1 stimulated with an AC when the sound pressure is 90 dB SPL in the external auditory canal.

The displacement amplitude for all measurement points in 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. The decrease in displacement amplitude of vibrations for frequencies above 2 kHz is related with different vibration phases in each measurement points on the RW membrane. An example 3D visualization of the vibration pattern of the RW membrane for one temporal bone specimens at 1 kHz, 2 kHz, 4 kHz and 8 kHz and 90 dB SPL in the external auditory canal is shown on Figure 2.

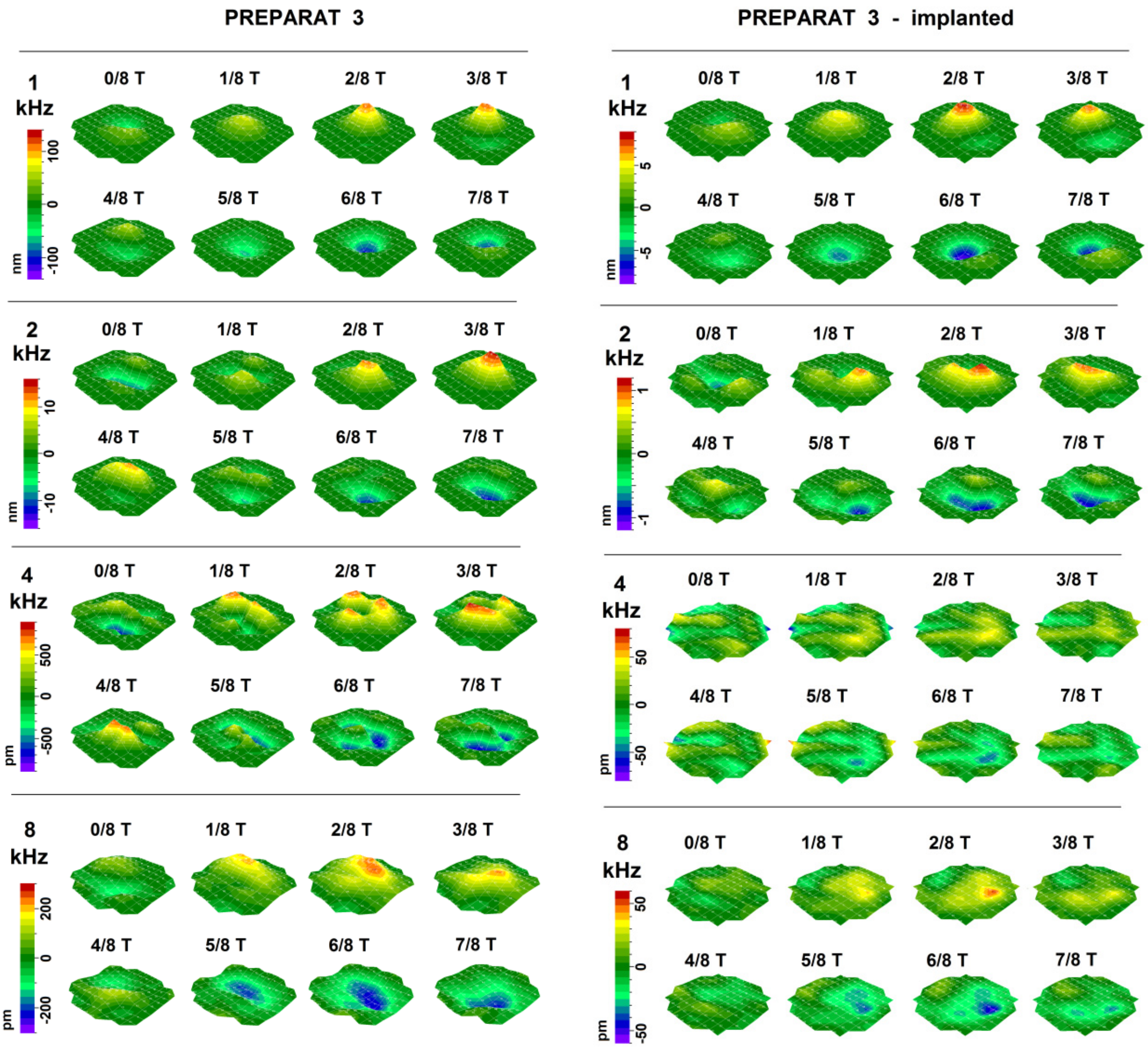

Fig. 2. The vibration pattern (3D visualization) of the RW membrane in specimen number 3 before and after Teflon piston prosthesis implantation. Visualization shows as eight pictures of period for various frequencies: 1, 2, 4 and 8 kHz. The results are shown for AC stimulation with a sound pressure level of 90 dB SPL in the external auditory canal. T – the period of vibration (T = 2π/f).

4. Discussion

The measurement results for the human ear RW membrane vibrations in four fresh cadaver temporal bone specimens for air conduction at 90 dB SPL in the external auditory canal showed that the maximum displacement amplitude for 1 kHz frequency in the central area of the RW membrane averaged 25 nm, whereas for 2 kHz, 4 kHz and 8 kHz frequencies it averaged 10 nm, 1.6 nm and 0.6 nm, respectively. The dispersion of the maximum vibration amplitude was related with different shapes and sizes of the RW membrane in each specimen, which is a characteristic trait of biological objects demonstrating individual variability. Based on 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.

Analysis of the measurements results revealed, that the vibration amplitude of the RW membrane after stapes Teflon piston prosthesis implantation, in comparison with the vibration amplitude in a physiological specimen was reduced several times. 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 changes 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 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

Results of conducted empirical research, shows the character of vibrations of the RW membrane in fresh human temporal bone specimens in their physiological condition. The obtained characteristics form a basis for differentiating hearing results achieved after surgical ossicular chain reconstruction. Findings presented in this paper will be of practical use in the development of a new type of stapes prosthesis.

Acknowledgements

The authors would like to thank the IPPH Director, Professor Henryk Skarzynski for granting permission to use facilities at the ICHS Head and Neck Clinical Anatomy Laboratory in Kajetany in order to conduct the research, prof. John J. Rosowski from Harvard-MIT, prof. Sunil Puria from Stanford University, dr Joe Sim and dr Michail Chatzmichalis from the ORL-Clinic, University Hospital in Zurich, for their valuable advice and tips regarding preparation methods of temporal bone specimens used for experimentation.

Research was funded by the Research Project Nr N N518 377637.

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