Round window membrane motion before and after stapedotomy surgery – an experimental study

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This paper presents the results of non-contact measurements of the human ear round window (RW) membrane motion in freshly harvested human cadaver temporal bone specimens. A PSV 400 Scanning Laser Vibrometer system (Polytec, Waldbronn, Germany) was used to determine the effect of stapedotomy on the sound-induced displacement amplitude of the RW membrane. The vibration patterns were measured in the frequency range of 0.4–10 kHz in four specimens with air conduction stimulation at 90 dB SPL applied to the external auditory canal. It was shown that the vibration amplitude of the RW membrane after stapes piston prosthesis implantation, in comparison with a physiological specimen, was reduced several times. The motion of the RW membrane can be used to determine the cochlear stimulation for the evaluation of middle ear ossicle reconstruction, especially in the case of otosclerosis surgery.

Key words: round window, vibration, laser Doppler vibrometry, stapedotomy

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 a primary role. In the AC process, the sound waves entering the concha auriculae are directed through the external auditory canal and contact the surface of the tympanic membrane causing it to vibrate. These vibrations are passed on through the ossicular chain (the malleus, the incus and the stapes). The vibrating footplate located in the oval window (OW) niche of the bony cochlea and attached by the annual ligament causes the perilymph, which fills the inner ear, to vibrate. Because the perilymph is incompressible, oscillations of the stapes cause round window membrane interaction.

It is assumed that the amplitude of the vibrations of the stapes and the volume of the vibrating fluid in the vicinity of the OW are a measure of the input impedance of the cochlea [1]–[4]. It has been empirically shown that for frequencies lower than 2000 Hz the volume of the vibrating fluid near the OW is the same as that next to the RW, where the vibrations take place in the opposite phase [5], [6]. 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 where a 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 footplate (stapedotomy or stapedectomy procedures). In the case where the manner of cochlea stimulation changes, the aforementioned stimulation can be examined by measuring the vibrations of the RW membrane maintained in the physiological condition [7].

The aim of this study was to estimate the effect of stapedotomy surgery on the relative change in the RW membrane motion before and after the stapes prosthesis implantation. The change in the RW membrane motion can be used to determine the change in the stimulation level of the cochlea caused by the surgical procedure, provided that the vibration pattern of the RW is the same before and after implantation.

2. Materials and methods

2.1. Human temporal bone preparation

In this investigation, 4 human temporal bones were studied. The temporal bones were harvested from human cadavers selected in the Forensic Medicine Department, Warsaw Medical University, within 2 days after death, in accordance with the standard Schuknecht methodology, useing a Stryker oscillating saw. After harvesting, the bones were kept in a saline solution at 5 ºC and frozen immediately upon extraction. The dissection was performed in the

perature of approx. 5 °C until the time of measurements, (iii) the measurements are taken within a 1–6 day period after death.

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 examination 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 the part of the facial nerve canal with the facial nerve) and making the round window and stapes visible, (5) gluing ER3-14A (Etymotic Research, Elk Grove Village, IL, USA) foam eartips onto the remaining bony rim around the tympanic annulus, (6) placing the ER7-14C (Etymotic Research, Elk Grove Village, IL, USA) microphone tube approx. 2 mm away from the tympanic membrane and an ER3-04 (Etymotic Reasearch, Elk Grove Village, IL, USA) loudspeaker adapter approx. 4–5 mm away in the ear mold, (7) periodically immersing the specimen in a saline solution to maintain a proper hydration of the structure. A diagram and the view of the temporal bone specimen prepared for examination according to the above mentioned method are presented in figure 1.
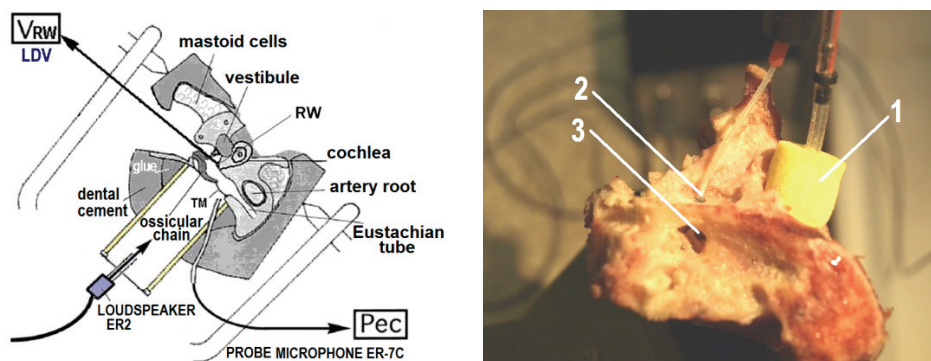

Fig. 1. Temporal bone preparation in physiological state in order to measure vibration of the round window membrane:
(a) scheme, (b) view. 1 – ER3-14A foam eartips in the external ear canal, 2 – ER7-14C probe tube of the microphone,
3 – RW membrane visible after having exposed hypotympanum in a special way

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Literature sources [3],[8]–[12] show that the functioning of middle ear structures in fresh cadaver temporal bones is the same as their functioning in the physiological condition, proved that the following three requirements are met: (i) the temporal bone specimens are harvested from human cadavers within 48 hours after death, (ii) the specimens are protected from drying and stored without being frozen at a tem-

After the measurements of the vibration parameters of the RW membrane in a physiological specimen, a stapes prosthesis was implanted in the same specimen. The implantation was performed without disturbing the tympanic membrane. Another measurement of the vibration parameters of the RW membrane in the post-implantation specimen was conducted immediately after mounting the prosthesis. The implantation procedure (figure 2) required: (1) immobilizing the footplate in the oval window with the aid of glass-ionomer cement, (2) cutting through the stapedius
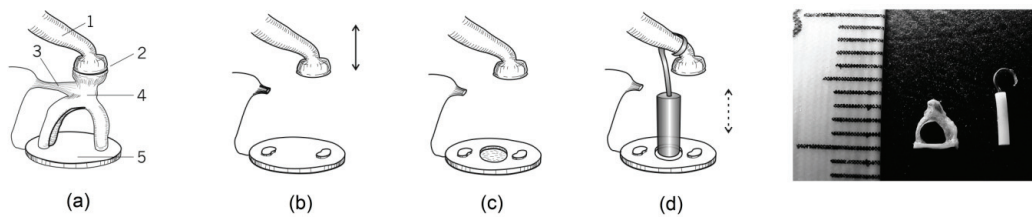
Fig. 2. Diagram of the stapedotomy with "teflon-piston" prosthesis implantation (on the diagram, for clarity, we omitted: glass-ionomer cement used for footplate immobilization and venous blood clot sealing the hole around the prosthesis) and the stapes and the prosthesis against the ruler with a scale of 1 mm: (a) anatomy of the stapes area: 1 – long crus of the incus, 2 – incudo-stapedial joint, 3 – stapedial muscle tendon, 4 – suprastructure of the stapes, 5 – footplate, (b) stapedial muscle tendon is amputated and the suprastructure of the stapes is removed, (c) a calibrated hole is made in the footplate, (d) "teflon-piston" type prosthesis is placed: the teflon piston is placed in the footplate hole, and the platinum ribbon is fixed to the long crus of the incus

muscle, (3) separating the stapes and incus in the incudo-stapedial joint, (4) removing the crura of stapes, (5) fenestrating the immobilized footplate (creating a hole of approx. 0.6 mm in diameter), (6) inserting the piston of the Teflon prosthesis into the calibrated hole and tightening a platinum ribbon on the long crus of the incus, (7) sealing the hole around the prosthesis with a venous blood clot, (8) maintaining a proper hydration of the structure during the prosthesis implantation, and not removing the inner ear fluid.

2.2. Measuring system

A block diagram and the view of the measuring system are shown in figure 3. During the measurements the reference beam frequency is compared with the beam reflected back of the object examined, whose frequency changes due to the Doppler phenomenon. Based on changes in frequency, the velocity of the vibrating object is determined.

The measuring station enables: (1) generating and transmitting an acoustic input signal in a 400 Hz–10 000 Hz frequency range and a sound pressure ranging from 40 dB to 100 dB SPL, (2) controlling and calibrating input signal parameters (frequency and SPL), (3) measuring displacement and velocity amplitudes and vibration phase.

Acoustic system: The acoustic input signal introduced into the substitute external auditory canal of the temporal bone specimen induces tympanic membrane vibrations and causes vibration of the ossicular chain. A sound is produced by a probe loudspeaker connected to an adapter placed in 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 ear mold placed in 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 (90 dB 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 ear mold,
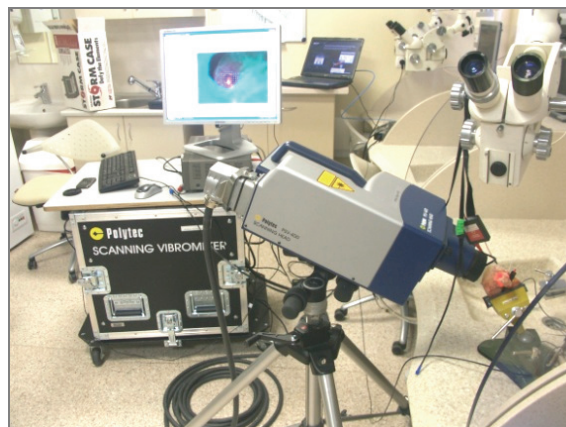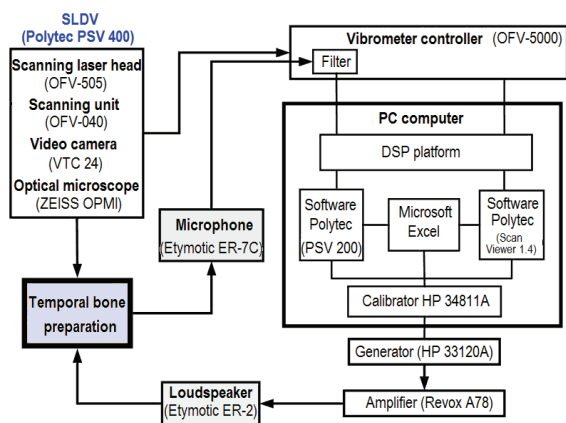

Fig. 3. Block diagram and the view of the measuring system

(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).

Optical system: The optical measuring system was based on a commercially available SLDV PSV 400 scanning laser Doppler vibrometer produced by Polytec GmbH, Waldbronn, Germany. The vibrometer is characterized by the following parameters: scanning surface of 512×512 measuring points, scanning laser head equipped with a 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 72× 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 a measuring data compiling system comprised of a PC computer with software and a generator of low-intensity signals.

2.3. Measuring methodology

The temporal bone specimen prepared in accordance with the procedure described in chapter 2.1 was fixed in an appropriate grip which allowed a precise arrangement of the specimen in relation to the laser measuring head. A pre-calibrated (ER-2, Etymotic Research) loudspeaker was attached to the (ER3-04, Etymotic Research) adapter connected to the (ER3-14A, Etymotic Research) foam eartips. The speaker was supplied with an input sound signal generated by a computer system (VIBSOFT, Polytec PI) and amplified by an acoustic amplifier (Revox A78).

An ER-7C microphone system was connected to the probe tube (ER7-14C, Etymotic Reasearch) placed in the specimen. The output signal from the microphone, after being amplified, was transmitted onto one of the input paths of the PSV400 laser-scanning vibrometer system. It generated the control feedback signal informing about the actual sound pressure level (SPL) in the external auditory meatus, at a distance of approx. 2 mm from the tympanic membrane. Based on the pressure level values registered by the microphone, adjustments were made to the amplification of the input acoustic signal transmitted to the speaker, so that a constant value of 90 dB SPL was maintained for all measuring frequencies.

The vibrometer controller was programmed to successively generate acoustic input signals with a center frequency of successive one-third octave bands: 400 Hz, 500 Hz, 630 Hz, 800 Hz, 1000 Hz, 1250 Hz, 1600 Hz, 2000 Hz, 2500 Hz, 3150 Hz, 4000 Hz, 5000 Hz, 6300 Hz, 8000 Hz, 10000 Hz. Respective measurements of the vibration speed at points evenly spread across the surface of the round window membrane of the aforementioned frequencies were taken. Figure 4 shows the part of the measuring station, as well as the measuring field without, and with, a grid of 93 measuring points.

Throughout the automatic measuring process a beam of light exciting the scanning measuring head was consecutively focused on measuring points additionally, the vibration speed and phase were subsequently measured in the chosen points. All measuring data was automatically saved on the computer's hard disk drive and subjected to processing in order to visualize and determine the amplitude-frequency and phase-frequency characteristics.

In order to prevent an impact of individual physiological differences between individual specimens on the results, the experiment was conducted in two stages: stage I – measurements taken in a physiologi-
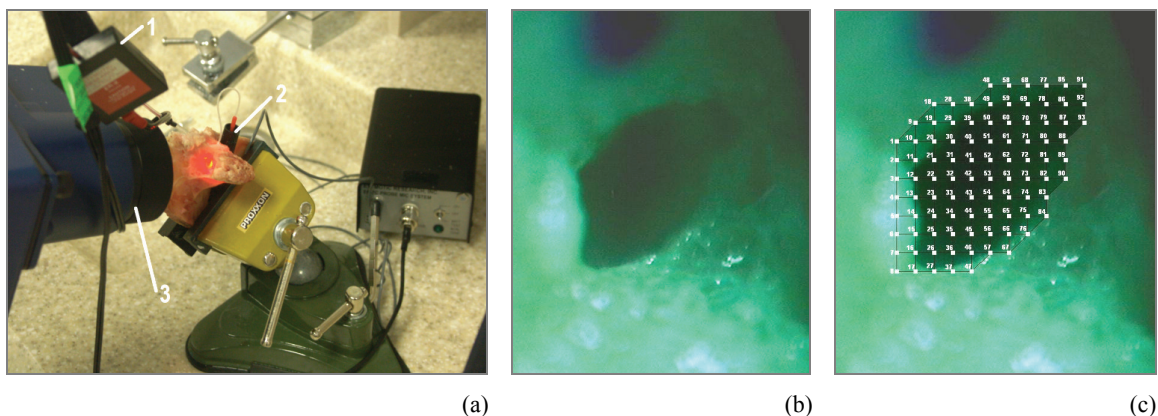

(a) (b) (c)

Fig. 4. (a) Photo of the part of the test stand: 1 – loudspeaker ER2, 2 – probe microphone ER-7C,
3 – scanning laser head OFV-505, (b) RW without a grid of measuring points, (c) the RW with 93 measuring points

cal 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), 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

The results of the original empirical research on 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 the frequencies ranging from 400 Hz to 10 kHz in the external auditory canal. The characteristics of the RW membrane vibrations were determined based on measurements of displacement in the measuring grid nodes. The amplitude–frequency characteristics of specimen Preparat 1 for targets located on the surface of the RW membrane

shown in figure 5. The displacement amplitude for all measuring 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. The decrease in the displacement amplitude of vibrations for frequencies higher than 2 kHz is related to different vibration phases in each measuring point on the RW membrane.
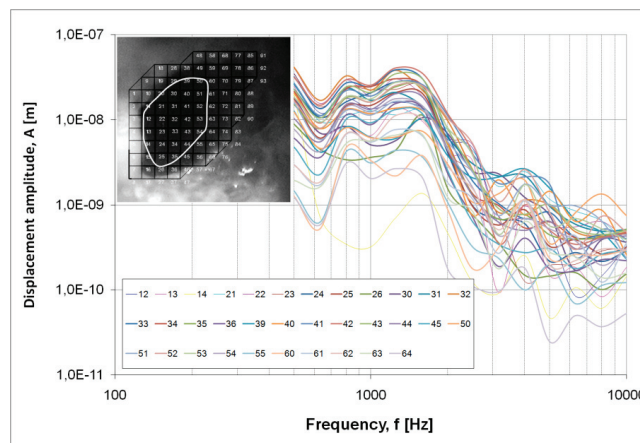

Fig. 5. Displacement amplitude of 34 measuring targets on the RW membrane when the sound pressure is 90 dB SPL in the external auditory canal. The result represents specimen Preparat 1 (physiological state) stimulated with an AC
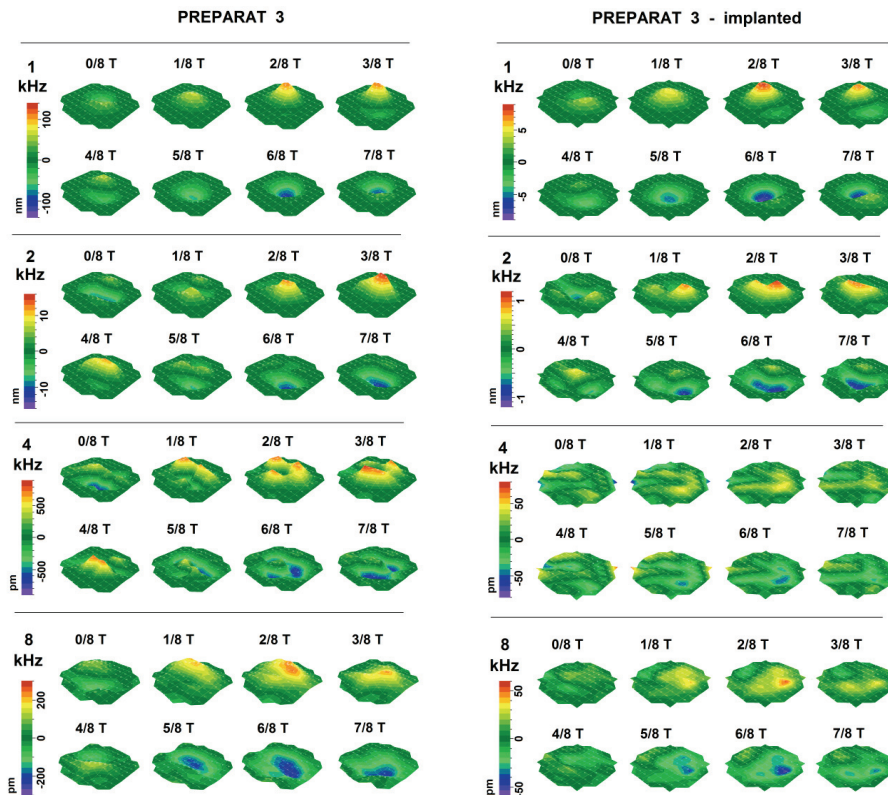

Fig. 6. The vibration pattern (3D visualization) of the RW membrane in specimen Preparat 3 before and after Teflon piston prosthesis implantation. Visualization shown as eight pictures of the period for various frequencies: 1, 2, 4 and 8 kHz. The results are shown for AC stimulation with a sound pressure level of 90 dB SPL in the external auditory canal. T – the period of vibration ($T = 2\pi/f$)

The RW surface displacement amplitude before and after stapes prosthesis implantation in the specimen Preparat 3 in one vibration cycle at different measuring frequencies is shown in figure 6. The results are presented in the form of 3D visualization of the vibration pattern at eight regular intervals, that is $1/8$ T (where T equals one vibration cycle time, $T = 2\pi/f$). In the physiological specimen at 1 kHz and 2 kHz vibration frequencies, all measuring 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. At 4 kHz and 8 kHz frequencies a significant difference between individual measuring points is observed. Examining the visualizations shown in figure 6 one should also take notice of a ten-fold decrease of the RW membrane maximum displacement amplitude for the implanted specimen (the appropriate amplitude values equal 9 nm, 1 nm, 80 pm) in comparison with the physiological specimen (the appropriate amplitude values equal 100 nm, 12 nm, 800 pm).

4. Discussion

The results of measuring 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 at a 1 kHz frequency in the central area of the RW membrane averaged 25 nm, whereas at 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 to different shapes and sizes of the RW membrane in each specimen, which is a characteristic trait of biological objects demonstrating individual variability. Based on a detailed iso-amplitude chart analysis it was found that the vibrations of measuring 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, the indications of both modal and travelling waves can be seen. 3D visualization shows that modal vibration was dominating at the low frequencies, and travellig 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. The analysis of the measuring 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 (figure 6). 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 the 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.

To our knowledge, no information regarding the vibration pattern of the human RW membrane has been reported for AC stimulation measured by Scanning Laser Doppler Vibrometry method. The vibration modes of the RW membrane corresponded closely to those reported in cats with time-averaged holography [13], [14]. KHANNA [13] and NOMURA [14] found the area of maximal displacement at low frequencies to be the antero-superior region of the RW, which is similar to our findings. They also reported substantial inter-subject variations in both magnitude and vibration pattern. Recently, STENFELT et al. [7] reported vibration measurements of the RW membrane in human temporal bone specimens using one-point LDV system. They created a matrix of reflective targets and measured their vibration on the RW membrane. Some differences exist between our data and that reported by STENFELT [7], especially in the maximum vibration amplitude at 1 kHz and 2 kHz in the specimen in physiological state. We suspect that the differences, which are not large, are due to different shapes and sizes of the RW membrane in the specimens, which is a characteristic trait of biological objects.

5. Conclusions

The results of the empirical research show the character of vibrations of the RW membrane in fresh human temporal bone specimens and the relative change in the RW membrane motion before and after the stapes Teflon piston prosthesis implantation (figure 6). *The stapes Teflon piston prosthesis leads to approximately 10-fold lower stimulation of perilymph*

vibration compared to physiological situation, at frequencies exceeding 2 kHz in particular. The characteristics obtained are the basis for differentiating hearing results achieved after surgical ossicular chain reconstruction. The findings presented in this paper will be of practical use in the development of a new type of stapes prosthesis.

Acknowledgement

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