

Differences in the perilymph fluid stimulation before and after experimental stapedotomy

MONIKA KWACZ^{1*}, MACIEJ MRÓWKA², JAROSŁAW WYSOCKI²

¹ Institute of Micromechanics and Photonics, Faculty of Mechatronics, Warsaw University of Technology, Poland.

² Institute of Physiology and Pathology of Hearing, Warsaw, Poland.

A stapedotomy surgery using a piston stapes prosthesis significantly modifies the perilymph fluid stimulation level and always leads to alteration of conditions in sound transmission through the cochlea. This paper shows the results of non-contact measurements of the stapes head velocity, a Teflon piston stapes prosthesis velocity and round window velocity conducted in freshly harvested human cadaver temporal bone specimens. The vibration patterns were measured within the frequency range of 0.4–10 kHz at the sound pressure level of 90 dB administered to the external auditory canal in the same specimen before and after experimental stapedotomy. It was shown that the vibrations of the stapes Teflon piston prosthesis and the physiological stapes are similar and approximately five-fold lower amplitude of the round window membrane vibrations compared to a physiologic situation is caused by piston shape of the stapes prosthesis. The results in this report are the part of a larger study designed to develop a new type of chamber stapes or whole middle ear prosthesis.

Key words: stapedotomy, Teflon piston stapes prosthesis, laser Doppler vibrometry

1. Introduction

Stapedotomy surgery, introduced by SHEA [1], [2], is generally considered to be a safe method for treating ossicular chain pathological conditions in which a stapes ankylosis occurs, especially in the case of stapedia otosclerosis [3]–[8]. The auditory results obtained after the stapedotomy should be generally perceived as satisfactory, but they are not identical for different stapes prostheses and individual frequencies of human auditory area. The auditory outcomes are expected to be better after stapedotomy with bigger piston diameters, for frequencies up to and including 2 kHz in particular [9]. Some authors claim that within the low and medium frequencies better outcomes are achieved after large fenestra stapedotomy or stapedectomy surgery [3], [4], [6]. The overclosure effect described by many researchers also refers rather to low and medium frequencies [4], [6], [7]. Despite

the range of clinical trials, the effects are poorly explained, mainly due to insufficient amount of experimental studies. It was shown that the pre- and post-stapedotomy values of round window membrane vibration parameters determining the intensity of sound transmission from the outer ear to the inner ear compartments are different [10], [11]. The differences were expected to occur particularly based on different sound frequencies. Stapes Teflon piston prosthesis implantation was found to cause several times lower amplitude of round window membrane vibrations compared to physiological situation, for frequencies above 2 kHz in particular. The change in the round window membrane motion testifies to the differences in the perilymph fluid stimulation level of the cochlea caused by the surgical procedure.

The objective of this study is to determine the reason of insufficient perilymph fluid stimulation level after the stapes piston prosthesis implantation. An additional objective is to determine the amplitude–

* Corresponding author: Monika Kwacz, Institute of Micromechanics and Photonics, Faculty of Mechatronics, Warsaw University of Technology, ul. św. Andrzeja Boboli 8, 02-525 Warsaw, Poland. Tel: +48 22 234 8447, fax: +48 22 234 8601, e-mail: m.kwacz@mchtr.pw.edu.pl

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frequency function for both the stapes head (pre-stapedotomy state) and the piston stapes prosthesis (post-stapedotomy state). The calculated functions will be used to optimize the structure of a new type of chamber stapes or whole middle ear prostheses.

2. Materials and methods

2.1. The specimen preparation

The studies were conducted on four human cadaver temporal bones. The temporal bones were harvested from human cadavers selected at the Forensic Medicine Institute of the Warsaw Medical University, within 2 days after death, in accordance with the standard methodology developed by Schuknecht, with the use of a Stryker oscillating saw. After being collected, the bones were kept in a saline solution at temperature of 5 °C and stored without being frozen until the following day. The dissection and vibration measurements were performed in the Head and Neck Clinical Anatomy Laboratory, International Center of Hearing and Speech, Kajetany, Poland. A detailed procedure for the specimen preparation has been described in our previous papers [10], [11]. Briefly, in our procedure of preparing the physiological specimen, the following steps are taken: (1) shortening the external auditory canal and placing an ER3-14A polyurethane foam ear plug (Etymotic Research, Elk Grove Village, IL, USA), (2) attaching an ER3-04 speaker adapter (Etymotic Research, Elk Grove Village, IL, USA) to the plug, (3) opening a one-mm diameter in the anterior wall of the external auditory canal to insert the ER7-14C microphone tube (Etymotic Research, Elk Grove Village, IL, USA), (4) performing a maximally wide posterior tympanotomy to obtain a wide approach to the oval window (OW) niche, (5) performing a wide insight into the round window (RW) niche through the jugular fossa, (6) periodically dipping the specimen in a saline solution.

2.2. Measuring system

In this study, a commercial SLDV PSV 400 scanning laser vibrometer developed by Polytec GmbH, Waldbronn, Germany (www.polytec.com) was used. The measuring system allows generating and administering an acoustic input signal to the loudspeaker, controlling and calibrating the input signal parameters

(frequency and the sound pressure level), as well as measuring the velocity and phase of the vibration of the middle ear structures, in this case especially the stapes head, the Teflon piston stapes prosthesis and the round window membrane.

A previously calibrated ER-2 loudspeaker (Etymotic Research, Elk Grove Village, IL, USA) was attached to the ER3-04 speaker adapter. The input acoustic signal generated by the computer system VIBSOFT (Polytec PI) was amplified by an acoustic amplifier (Revox A78). The sound intensity level of the input acoustic signal was controlled by an ER-7C probe microphone (Etymotic Research, Elk Grove Village, IL, USA) placed in the microphone tube at a distance of 2 mm from the tympanic membrane. Based on the SPL value measured by the microphone we corrected the amplification of the input acoustic signal supplied to the loudspeaker to maintain the constant SPL value of 90 dB for each of the measuring frequencies within a 0.4–10 kHz frequency range.

2.3. Measuring procedure

The vibrometer controller was programmed to successively generate acoustic input signal with a center frequency of successive one-third octave bands: 0.40 kHz, 0.50 kHz, 0.63 kHz, 0.80 kHz, 1.00 kHz, 1.25 kHz, 1.60 kHz, 2.00 kHz, 2.50 kHz, 3.15 kHz, 4.00 kHz, 5.00 kHz, 6.30 kHz, 8.00 kHz, and 10.0 kHz. At the first stage the measurements of the vibration parameters of both the stapes head and the round window membrane were recorded in normal anatomy conditions. Then, in the same specimen, the experimental stapedotomy procedure with a standard Teflon piston stapes prosthesis (DEMED® sp. z o.o., Mikołów, Poland) was performed. The implantation procedure has been described in our previous papers [10], [11].

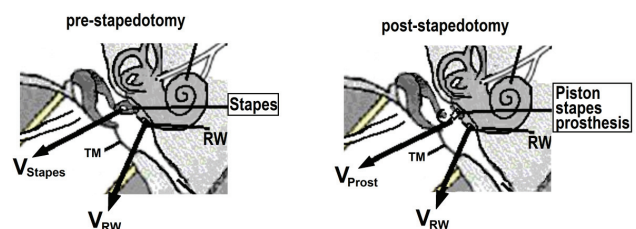


Fig. 1. Scheme of measuring procedure. Left: the first stage. Recording the vibration parameters of the stapes head (V_{Stapes}) and the round window membrane (V_{RW}) in normal anatomy condition (pre-stapedotomy). Right: the second stage. Recording the vibration parameters of the piston stapes prosthesis (V_{Prost}) and the round window membrane (V_{RW}) after prosthesis implantation (post-stapedotomy)

Immediately after prosthesis implantation another series of both prosthesis piston and RW vibration recordings was performed. Figure 1 presents the scheme of the measuring procedure.

3. Results

Amplitude–frequency profiles of specimen 1 in the pre-stapedotomy state for 73 points on the surface of the stapes head are shown in figure 2 (left). The displacement amplitude of all the measuring points is decreased from the level of $1.0\text{--}5.0 \times 10^{-8}$ m at frequencies within the range of 0.4–1.0 kHz to the level of $1.0\text{--}9.0 \times 10^{-11}$ m at frequencies within the range of 9.0–10.0 kHz. Only at a frequency of 3150 Hz a rapid decline of the displacement amplitude of the stapes head is observed. The typical resonant frequency of the middle ear conducting apparatus is observable at 0.8 kHz. The dispersion of the values of displacement amplitude exceeding 2 kHz is related to different vibration phases of individual stapes head vibration measuring points, which is demonstrated in the form of three-dimensional visualisation (figure 3, left). Figure 2 (right) presents the amplitude–frequency characteristics of specimen 1 in the post-stapedotomy state for 38 points on the surface of the Teflon piston stapes prosthesis. The displacement amplitude of all the measuring points is decreased from the level of $1.0\text{--}5.0 \times 10^{-8}$ m at frequencies within the range of 0.4–1.0 kHz to the level of $2.0\text{--}10.0 \times 10^{-11}$ m at frequencies within the range of 9.0–10.0 kHz. The rapid decline at a frequency of 3150 Hz is not observed. Within the range from 1.6 kHz to 4 kHz the displacement amplitude of the piston stapes prosthesis is

higher than the displacement amplitude of the stapes head. At the frequency of 1250 Hz a slight decline of the displacement amplitude of the stapes prosthesis is observed. The typical resonant frequency of the middle ear conducting apparatus is again observable at 0.8 kHz. Dispersion of the values of displacement amplitude exceeding 2 kHz is related to different vibration phases of individual stapes prosthesis vibration measuring points, which is demonstrated in the form of three-dimensional visualisation (figure 3, right).

Figure 3, left, presents the stapes head surface velocity amplitude of specimen 1 at different measuring frequencies (0.5 kHz, 1.0 kHz, 2.0 kHz, 3.15 kHz, 4.0 kHz, 6.3 kHz, 8.0 kHz and 10.0 kHz). For frequencies below 2 kHz vibrations of all the stapes head points occurred in the same phase and showed the values of maximum velocity amplitude at the level of $50\text{--}80 \mu\text{m/s}$. This indicates that stapes movement within this frequency range is piston-like. For frequencies above 2 kHz a significant difference was observed in the vibration phases of individual measuring points which proves that stapes movement is rocking-like. The values of maximum velocity amplitude above 2 kHz decreased to the level of $25\text{--}40 \mu\text{m/s}$. Figure 3, right, presents the Teflon piston stapes prosthesis velocity amplitude of specimen 1 at different measuring frequencies (0.5 kHz, 1.0 kHz, 2.0 kHz, 3.15 kHz, 4.0 kHz, 6.3 kHz, 8.0 kHz and 10.0 kHz). For frequencies below 2 kHz vibrations of all the stapes prosthesis points occurred in the same phase and showed comparable values of maximum velocity amplitude at the level of $70\text{--}90 \mu\text{m/s}$. This indicates that stapes prosthesis movement within this frequency range is piston-like. For frequencies above 2 kHz a significant difference was observed in the vibration phases of

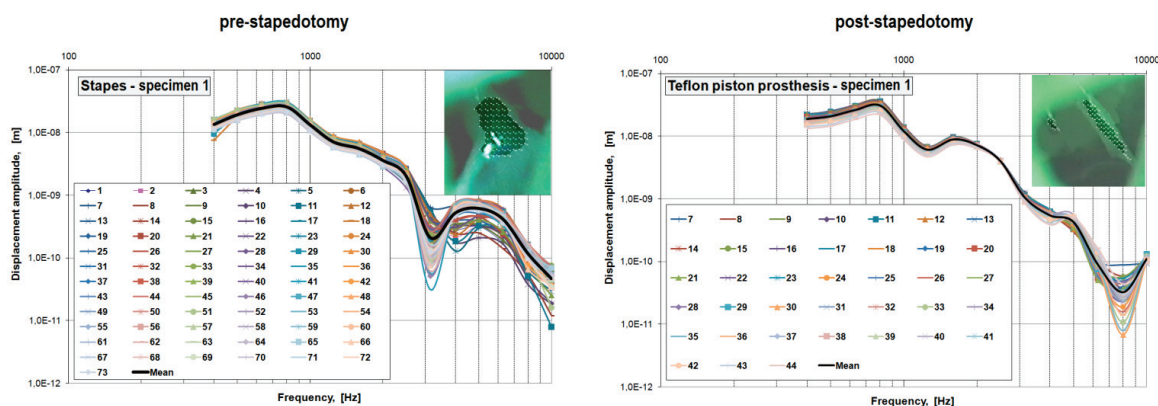


Fig. 2. Amplitude–frequency profiles of specimen 1 while exposing the tympanic membrane to a sound of 90 dB SPL. Left: Magnitude of the displacement amplitude for 73 points on the surface of the stapes head (pre-stapedotomy state). Right: Magnitude of the displacement amplitude of 38 points on the surface of the Teflon piston stapes prosthesis (post-stapedotomy state)

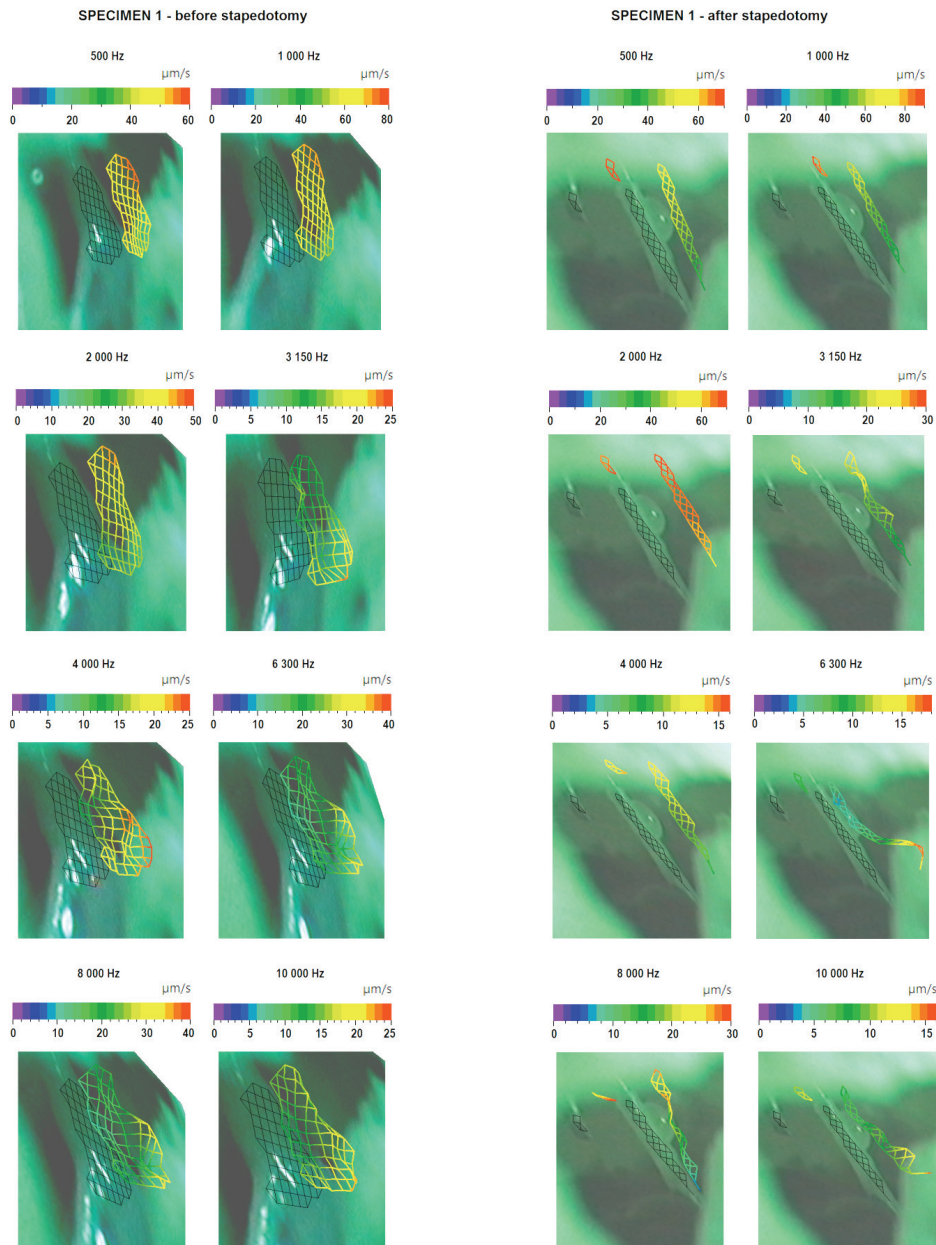


Fig. 3. Three-dimensional visualization of velocity amplitude for specimen 1 while exposing the tympanic membrane to a sound of the following frequencies: 0.5 kHz, 1 kHz, 2 kHz, 3.15 kHz, 4 kHz, 6.3 kHz, 8 kHz, and 10 kHz, and an SPL of 90 dB.

Left: Stapes head surface velocity amplitude of 73 points (pre-stapedotomy state).

Right: Teflon piston stapes prosthesis velocity amplitude of 38 points (post-stapedotomy state)

individual measuring points which proves that stapes prosthesis movement is rocking-like. The values of maximum velocity amplitude above 2 kHz decreased to the level of 15–30 $\mu\text{m/s}$.

Figure 4 presents the amplitude–frequency characteristics of specimen 1 for points on the surface of the round window membrane (left – pre-stapedotomy state, right – post-stapedotomy state). The typical resonant frequencies of the middle ear conducting apparatus are observable. A decrease in the amplitude of vibrations exceeding 2 kHz is related to different vibration phases of individual RW membrane vibra-

tion measuring points, which is demonstrated in the form of three-dimensional visualisation (figure 4 in [11]) and in isoamplitude diagrams (figure 5 in [11]). Within the range of low frequencies from 0.5 kHz to 2 kHz the displacement amplitudes of all the measuring points are 10–15-fold higher than those within the range of frequencies from 2 kHz to 10 kHz for pre-stapedotomy state and 15–20-fold higher for post-stapedotomy state. The pre- and post-stapedotomy results demonstrated approximately 5-fold decrease of RW membrane vibration amplitudes in the specimen with an implanted prosthesis compared to the vibra-

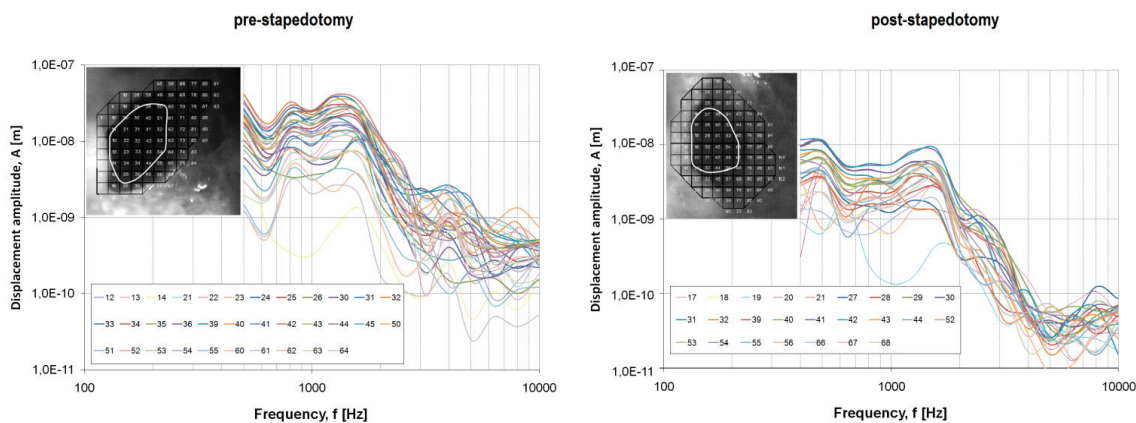


Fig. 4. Amplitude–frequency characteristics of specimen 1 for points on the surface of the round window membrane while exposing the tympanic membrane to a sound of 90 dB SPL. Left: Round window membrane surface displacement amplitude of 34 points for pre-stapedotomy state. Right: Round window membrane surface displacement amplitude of 25 points for post-stapedotomy state

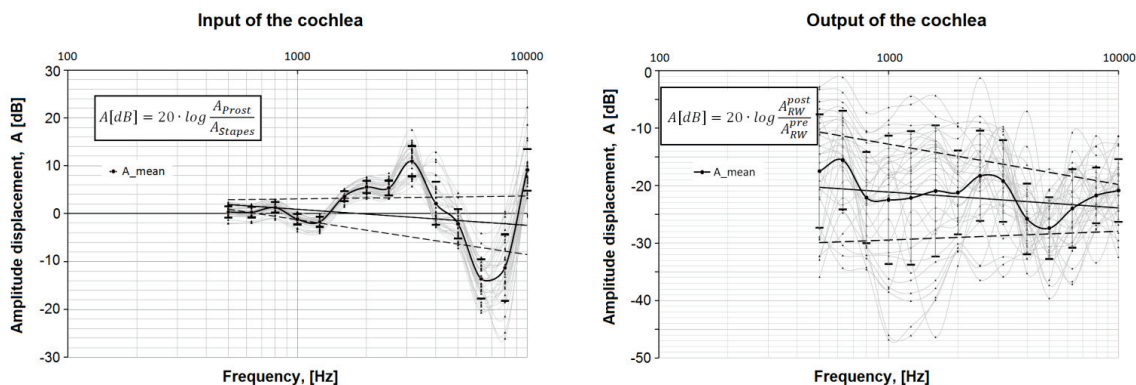


Fig. 5. Post-stapedotomy to pre-stapedotomy ratio of displacement amplitude for the cochlear input (left) and the cochlear output (right) represented in SPL decibels according to the following formula: $A [dB] = 20 \log(A_1/A_0)$, where index 1 refers to the post-stapedotomy state, and index 0 refers to the pre-stapedotomy state. The figures present average values of vibration amplitude changes of the selected measuring points on the stapes head, stapes prosthesis and RW membrane for 4 subsequent specimens (black triangles) joined into curve lines (thin, grey, solid curved lines) and the values of average vibration amplitude of all the points for all specimens ($A - \text{mean}$, thick, black, solid curved line) with standard deviation markers joined with a thin, vertical line. Tendencies in the form of simple regressions were determined: a black, single, solid line for the average amplitude value and black, dashed, straight double line for the average amplitude value with standard deviation $\pm SD$

tion amplitude in the specimen maintained in physiological condition. This indicates that the Teflon piston stapes prosthesis leads to approximately 5-fold lower stimulation of perilymph vibration compared to physiological situation.

The total results for four specimens in the form of average post-stapedotomy to pre-stapedotomy ratio of displacement amplitude A [dB] for both cochlear input and cochlear output vibration amplitude with individual results and standard deviation are presented in figure 5. Showing fluctuation, depending on frequency, the determined average ratio for the cochlear input stays at the same level close to 0 dB. Within the range from 1.6 kHz to 4.0 kHz the average ratio value is above 0 dB (max. +10 dB at 3.15 kHz) and within

the range from 5.0 kHz to 8.0 kHz it is below 0 dB (max. –14 dB at 6.3 kHz). The standard deviation from the average value increases with growing frequencies and reaches the values of approx. ± 2 dB within the 0.5–2.5 kHz frequency range and approx. ± 6 dB at frequencies of 3.15–10.0 kHz. The determined average ratio for the cochlear output generally decreases, which results from a decrease in vibration amplitude following implantation compared to vibration amplitude before the experimental prosthesis implantation. The standard deviation from the average value declines with growing frequencies and reaches the values of approx. ± 10 dB within the 0.5–1.6 kHz frequency range and approx. ± 5 dB at the frequencies of 2.0–10.0 kHz. This implies that perilymph

vibration stimulation and further RW membrane vibration stimulation by the stapes prosthesis are 5-fold lower compared to the pre-stapedotomy situation and decline with a growing frequency of the sound administered to the external auditory canal.

4. Discussion

The measuring results for the stapes head, the Teflon piston stapes prosthesis and the round window membrane recorded in four human cadaver temporal bones showed the differences in the perilymph fluid stimulation level before and after stapedotomy surgery. The results obtained by other authors confirm the reliability of the obtained data for interpreting clinical data. As was demonstrated in literature sources [12]–[17], the auditory organ in the fresh cadaver temporal bones behaves similarly to that in physiological condition, provided that the temporal bone specimens are harvested from human cadavers within 48 hours after death, are protected from drying and stored without freezing until the measurements, and the measurements are performed within 1–6 days after death [13]–[16].

We used a laser Doppler vibrometry technique to measure velocity and displacement amplitude of middle ear components. This technique is commonly used to assess real-time fast vibrations by non-contact method and especially useful for small objects. This type of studies has been conducted for several years based on human cadaver temporal bones, among others, to understand mechanical properties of the ossicular system better [12], [18], [19], to understand the influence of some pathologies [20] or improve the prostheses used in otosurgery [21]–[23]. All the studies of this type are based on the records of ossicular system vibrations and/or window vibrations or on observation of pressure changes within the inner ear fluid compartments.

It is assumed that the amplitude of the stapes vibration and the motion of the round window membrane can be used to measure the cochlear stimulation for the evaluation of middle ear ossicular chain reconstruction [12], [19], [24]–[27]. This is especially crucial in a situation where 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). The same assumption was accepted in our study, and post-stapedotomy to pre-stapedotomy ra-

tios of displacement amplitude for the cochlear input and the cochlear output were calculated (figure 5). These ratios indicate that perilymph fluid stimulation level after stapedotomy surgery is five-fold lower compared with that in normal physiological condition despite the fact that stapes and stapes prosthesis amplitude vibrations are similar. Therefore one can assume that stapedotomy surgery with a standard Teflon piston stapes prosthesis causes incomplete closure of the air–bone gap resulting in poor hearing outcomes, especially at the frequencies above 2 kHz. This fact proves the need for developing a new type of stapes or whole middle ear prosthesis which will better stimulate the perilymph fluid in the cochlea. We are now working on optimizing a new chamber prosthesis and planning to use the amplitude–frequency functions for both stapes and piston stapes prosthesis (figure 2) to create a 3D finite element model of the sound transmission through the inner ear. This model will be described in our further articles.

5. Conclusions

The stapes Teflon piston prosthesis vibrates similarly to the normal stapes and approximately five-fold lower stimulation of the perilymph vibration compared to physiological situation is caused by piston shape of the stapes prosthesis. The findings presented in this paper will be of practical use in the development and optimizing of a new type of chamber stapes or whole middle ear prosthesis.

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