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Research paper

Effect of different stapes prostheses on the passive vibration of the basilar membrane

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ABSTRACT

The effect of different stapes prostheses on the basilar membrane (BM) motion was determined. To that end, a three dimensional finite element (FE) model of the passive human cochlea was developed. Passive responses of the BM were found based on coupled fluid–structure interactions between the cochlear solid structures and the scala fluids. The passive BM vibrations in normal (healthy) cochlea were compared with vibrations in the cochlea in which a 0.4-mm piston or a proposed new type of prosthesis was implanted. The proposed chamber prosthesis was not experimentally implanted, but only numerically simulated. Design of the new chamber stapes prosthesis is presented for the first time in this paper. The simulation results showed 10–20 dB decrease in BM displacement amplitude in the case of the piston. In contrast, the BM responses in the cochlea with the new prosthesis are higher with respect to the healthy ear. The results obtained in this study are promising for further research to optimize the design of the new chamber stapes prosthesis.

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1. Introduction

Piston stapes prostheses are commonly implanted in patients with conductive or mixed hearing loss caused by stapes otosclerosis. Their role is to stimulate the perilymph for hearing restoration. In stapedial otosclerosis, abnormal bone growth in the oval window niche or ankylosis of the stapedio-vestibular joint reduces the ability of the stapes to vibrate. This changes the function of the normal ossicular chain, and always leads to conductive hearing loss with a tendency to progression (Dubreuil et al., 1994; Häusler, 2004; Møller, 2007).

Stapedotomy surgery, introduced by Shea (Shea, 1958; Shea et al., 1962), is generally recognized as a relatively safe and efficient surgical technique for treating clinical otosclerosis (Rizer and Lippy, 1993; Dubreuil et al., 1994; Häusler, 2004; Somers et al., 2006; Vincent et al., 2006; Møller, 2007).

Stapedotomy involves removing the suprastructure of the otosclerotic stapes, drilling a small hole in the center of the immobilized SF, placing the piston of the stapes prosthesis into the hole and tightening a wire or a ribbon on the long process of the incus. The prosthesis transmits vibrations from the incus directly to the cochlear fluid, effectively bypassing the immobilized stapes. The longitudinal vibration of the piston mimics the vibration of the normal stapes footplate, generates a pressure wave into the cochlea and activates the sensory hair cells.

Typical stapes prosthesis consists mainly of two parts. The first is a cylindrical piston, designed to fit into the SF opening. Initially the diameter of the pistons was 0.8 and 0.6 mm. Recently there is a tendency to reduce the diameter of the piston from 0.8 mm down to 0.3 mm in order to reduce the risk of inner ear damage. Influence of the piston diameter on post-operative hearing results has been described in few works. According to some of these works, diameters less than 0.4 mm are not recommended (Grolman et al., 1997; Hüttenbrink, 2003). Many, but not all, authors have stated that the piston with a larger diameter gives better hearing improvement (Fisch, 1982; Grolman et al., 1997; Shabana et al., 1999; Sennaroğlu et al., 2001; Marchese et al., 2007; Laske et al., 2011). The discrepant results one can explain by the effect of the tissue seal on the vibrational energy in the fenestra or by the shift in resonance frequency due to the different mass of the prostheses (Rosowski and Merchant, 1995; Hüttenbrink, 2003). The pistons are

Abbreviations: AL, annular ligament; BM, basilar membrane; CF, characteristic frequency; d_{BM}, displacement amplitude of the basilar membrane (model-derived); d_{SF}, displacement amplitude of the stapes footplate (from experiment); d_{prost}, displacement amplitude of the piston stapes prosthesis (from experiment); *f*, frequency; FE, finite element; RWM, round window membrane; SF, stapes footplate; SPL, sound pressure level; ST, scala tympani; SV, scala vestibuli

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currently composed of titanium, polytetrafluorethylene (PTFE), stainless steel or gold. It was shown (Tange et al., 2004) that the heavier gold piston (diameter, 0.4 mm; weight, 10.2 mg) gives more cases of overclosure (28.3%) than the lightweight (diameter, 0.4 mm; weight, 2.5 mg) titanium piston (9.4% cases of overclosure).

The second part of the stapes prosthesis is an attachment mechanism, which may be a wire or ribbon, designed to be crimped around the anchoring ossicle (incus or malleus). Correct crimping is crucial to maximizing energy transfer and ensures good post-operative hearing results. Inaccurate crimping (either too loose or too tight) may lead to loose-wire syndrome (hearing loss, poor speech discrimination, distortion of sound). Too tight crimping often causes incus erosion with loosening of the prosthesis (McGee, 1981). As shown by Huber et al. (2003), tight crimping leads to improved functional results because of better sound transmission at the incus–prosthesis interface. In this case, the improvement in the air-bone gap closure is in the range of 3 dB pure-tone average. With loose crimping or no crimping, the amount of the residual loss largely varies, possibly reaching up to 28 dB.

Over time, there were many modifications in material and design of the stapes prosthesis, especially of the attachment mechanism. Nevertheless, the piston-shape prosthesis remains the dominant prosthesis in use today. The hearing results obtained after stapedotomy surgery are generally perceived as good. However, the good overclosure effect described by the majority of researchers mainly affects low (0.5 kHz) and medium frequencies (1 kHz and 2 kHz) and a large number of patients report a lack of satisfactory results for frequencies above 2 kHz (Rizer and Lippy, 1993; Häusler, 2004; Somers et al., 2006; Vincent et al., 2006). Wysocki et al. (2011) have shown experimentally that the stapes piston prosthesis leads to an approximately 14 dB lower perilymph vibration at RW compared to the physiological situation, in particular at frequencies exceeding 2 kHz. Similar results were obtained by Sim et al. (2012). It was also reported by Kwacz et al. (2012) that the vibration amplitudes of the normal stapes head and the piston prosthesis are nearly of the same magnitude (for frequencies below 4 kHz) and that the lower stimulation of perilymph by the piston compared to the stimulation by the normal SF is caused by the smaller piston area. The 14 dB lower stimulation may provide an explanation for the lack of the expected auditory outcomes after stapedotomy surgery, especially for frequencies above 4 kHz. The frequency-dependent hearing results are related to the displacement amplitude of the BM (d_{BM}) at the characteristic frequency (CF). For frequencies above 4 kHz, d_{BM} magnitude may generate a reduced action potential resulting in reduced hearing, especially at low sound pressure levels.

A dynamic fluid–structure interaction occurs when the cochlea is stimulated by vibrating stapes or piston of the stapes prosthesis. The stapes vibration results in a pressure change in the cochlear fluid (Peterson and Bogert, 1950). Due to interaction between the inertia of the fluid chambers and the BM stiffness, this pressure wave elicits traveling waves on the BM, which travels from the basal to apical end of the cochlea and peaks at a frequency-dependent position. The term traveling waves refers to the BM displacement waves, which are slower by orders of magnitude than the speed of sound in the cochlear fluids. It is commonly accepted that traveling waves are directly related to the passive material parameters (density, stiffness, and damping) of cochlear tissues and fluids and constitute the first stage of frequency filtering of auditory signals. The motion of the BM ultimately stimulates the mechanosensory receptors of the organ of Corti and provides frequency discrimination of the sound stimuli. The position of the maximum BM displacement amplitude depends on the stimulus frequency and occurs at a location where the natural frequency of the BM corresponds to this stimulus frequency (von Békésy, 1960, 1970; de Boer, 1996; Ulfendahl, 1997; Robles and Ruggero, 2001). When the cochlea is functioning normally, and during higher levels of stimulation (>40 dB, when passive cochlear mechanics is predominant for perception), the peak displacement amplitude of the BM is boosted by 20–30 dB compared to the displacement amplitude of the stapes footplate (Gundersen et al., 1978; Robles and Ruggero, 2001; Stenfelt et al., 2003). Introducing a piston of the stapes prosthesis into the hole in the immobilized SF may potentially change the passive vibration of the BM, especially the amplitude–frequency response of the BM. This fact may provide an explanation for the lack of expected hearing results after stapedotomy surgery. Despite a range of experimental and modeling studies on cochlear macromechanics, there is still limited information on the BM motion after stapedotomy surgery, mainly due to the perilymph stimulation through the piston prostheses have not been studied in a systematic manner.

The aim of this study was to assess the effect of various types of stapes prostheses on the BM vibration and estimate the post-operative outcomes using the earlier developed 3D finite element (FE) model of the human inner ear (Kwacz et al., 2013). In that previous work, we demonstrated a piston-induced decrease of 15 dB in the round window membrane (RWM) vibration compared with normal anatomical condition. Here, we extend the previous research to investigate the BM vibration. By comparing the BM response of the normal ear to that with prosthesis inserted, it is expected that advances can be made in improving the design of new stapes prosthesis.

An additional objective of the study was to simulate both the BM and the RWM vibration after stapedotomy using a new type of stapes prosthesis currently under investigation at Warsaw University of Technology. The parameters calculated may be used to optimize the geometry of the prosthesis in order to achieve a similar intensity of sound transmission as in the case of the healthy ear.

2. Methods

The effect of piston stapes prosthesis on the passive vibration of the BM was studied using a three-dimensional FE model of the uncoiled cochlea. The modeling studies include the BM vibrations in a frequency range between 400 Hz and 10 kHz in both the pre-stapedotomy and the post-stapedotomy state. In the post-stapedotomy state, the differences in the BM motion were studied for the piston prosthesis of 0.4 mm diameter and for the new chamber stapes prosthesis. The numerical results derived from the FE model were compared with the measurement results obtained from experiments in human temporal bones.

2.1. Three-dimensional FE model of the cochlea

2.1.1. The pre-stapedotomy model

A three-dimensional FE model of the cochlear macromechanics was recently developed, adjusted and validated by Kwacz et al. (2013). The model consists of two straight fluid channels, representing the scala vestibuli (SV) and scala tympani (ST), separated by the BM. The third channel (scala media) was included in the SV. The Reissner's membrane and the micromechanical structures of the Organ of Corti were omitted in the model. The SF was attached to the SV in the oval window by an annular ligament (AL) and the ST was connected to the middle ear cavity at the round window niche by the RWM. The SV and the ST were filled with a small-compressible viscous perilymph fluid. At the apex, these two channels were connected to each other through the helicotrema.

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