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Bone Conduction in a Three-Dimensional Model of the Cochlea

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Key Words

Bone conduction · Cochlea · Cochlear mechanics · Finite elements

Abstract

Hearing sensations are caused by air- and bone-guided sound. Of course, other biological materials like tendons, muscles and tissue are also involved during conduction of sound. To study the influence of bone conduction, a formerly developed finite element model was excited by harmonic pressure signals at the cochlea wall. The clinical finding during middle ear surgery, namely the increase in bone conduction sensitivity with removed footplate, was confirmed. Other psychoacoustic effects with bone conduction are described in the early experiments by Bárány, who proved the cancellation of air- and bone-conducted sound in humans. The simultaneous stimulation of the cochlea wall and the phase-reversed stimulation of the stapes footplate in the finite element model confirmed his findings. Further clues to the solution of unsolved problems in audiology and middle ear pathology are given.

Introduction

In order to better understand bone conduction (BC) hearing, the wave propagation along the basilar membrane (BM) with BC stimulation must be known. Though this problem had already been addressed, the physics was mostly covered by one-dimensional considerations [1]; however, these are not able to include the complex geometry of the cochlea sufficiently. Therefore, we developed a three-dimensional model of the cochlea and stimulated the bony wall surrounding the fluid by different pressure signals [2]. Herewith, we were able to simulate different states in middle ear surgery and early findings in the physiology of BC.

A result which confirms clinical findings in middle ear surgery is the increase in BM displacement with BC stimulation when the stapes footplate is removed during stapedectomy. An example from audiology is the cancelling of hearing sensation when sound is presented by air conduction (AC) and BC simultaneously.

Methods

To calculate the BC response, we used a formerly developed finite element model of the cochlea [2].

Figure 1 shows the complete discretized finite element model with the stapes footplate and the round window at the base of the cochlea. The BM inside the cochlea with its characteristic gradients of width and thickness is presented in figure 2. The results shown in figures 5 and 6 are the maximum displacements which occur with one stimulation frequency at one point along the BM. Instead of the usual stapes footplate stimulation of the middle ear, the outer bony wall of the cochlea surrounding the perilymphatic fluid was stimulated (fig. 3). As the outer cochlea wall (OCW) was not represented by an extra material, pressure was applied to those areas which confine the fluid elements.

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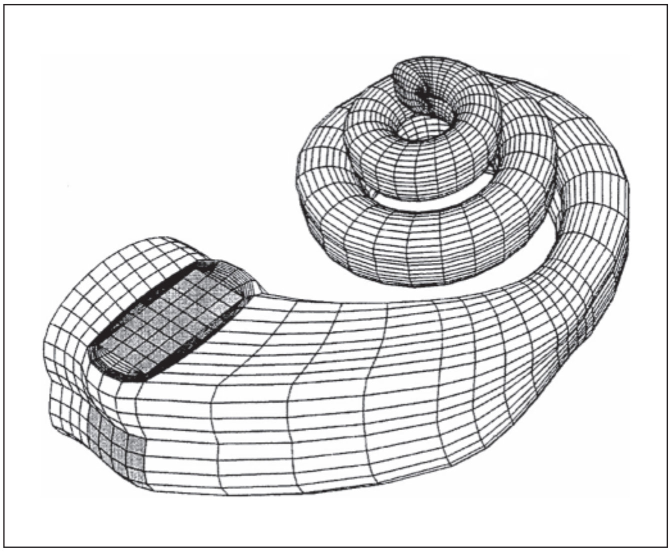

Fig. 1. The curved finite element model of the cochlea includes the fluid structure coupling of the nonviscous and nearly incompressible lymph and the BM. The dark oval window in the annular ligament has a length of 3 mm and a width of 1.4 mm. The gray round window can be seen under the oval window.

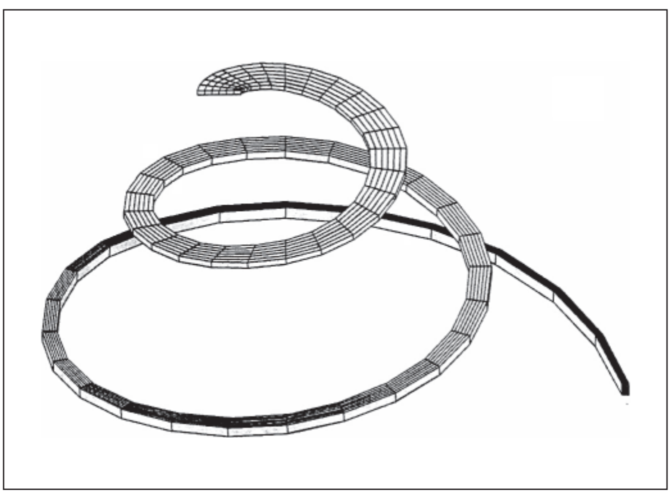

Fig. 2. The BM is idealized as an orthotropic elastic shell and has a width of 0.08 mm at the base and increases to 0.5 mm at the end near the helicotrema. Gradients like the BM width or the BM thickness are easily considered with the finite element model.

Stimulation by external pressure is easy, but the specification of an externally applied displacement is not. To obtain a displacement at the OCW, in principle the number of local coordinate systems must be as high as the number of finite elements. Because this is unrealistic, an additional bone layer might be inserted around the perilymph and stimulated on the plane surfaces [3; Taschke, H., pers. commun.].

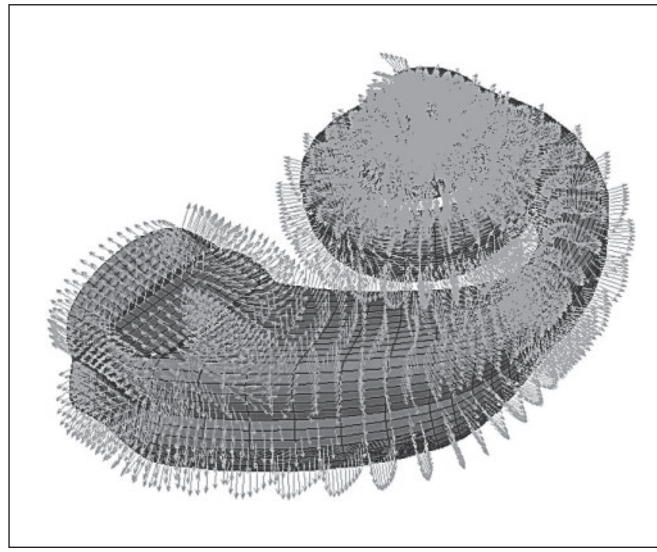

Fig. 3. The arrows represent the loading by external pressure with BC. It is easy to apply external pressure, but the specification of externally applied displacements is not, as this theoretically requires an equal number of local coordinate systems and finite elements.

For this reason, we were only able to stimulate the cochlea by pressure. It is possible to calculate mechanical impedances because the velocity of vibrating structures can be acquired by multiplication of the displacement by the imaginary unit j and the angular frequency ω as the system is linear.

Results

Three results with BC and AC stimulation are presented.

Traveling Wave Propagation in the Cochlea

The analogy of frequency-dependent maximum BM displacement with BC and AC stimulation, which has recently been found in experiments with human cadavers [4], has been confirmed. This result of our finite element model evaluation is only stated here and not further documented explicitly.

Cancellation of AC and BC; Decrease in BM Displacement by Simultaneous Phase-Shifted Stimulation of AC and BC

A surprising result is the cancellation of hearing sensation with simultaneously applied AC and BC. The ear-

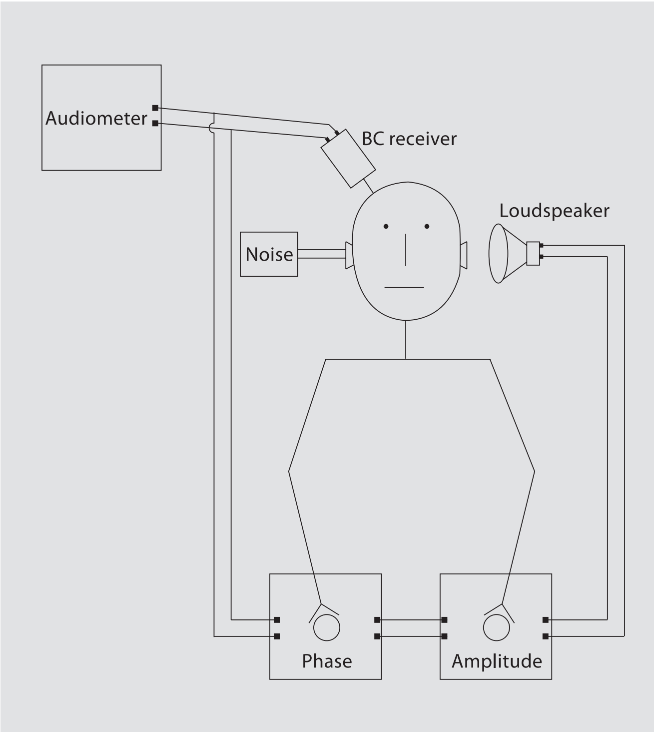

Fig. 4. The experiments by Bárány [5] demonstrated the possibility of cancellation of air- and bone-conducted sound. Amplitudes and phases had to be tuned carefully by the subjects.

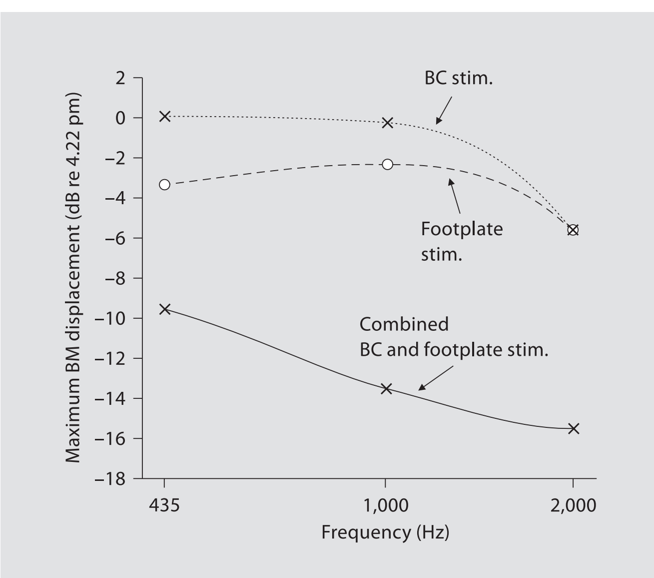

Fig. 5. The calculated maximum BM displacement is plotted as a function of frequency. Bone-conducted sound is reduced by approximately 14 dB at 1,000 Hz.

ly experiment by Bárány [5] supports the assumption of mutual erasement of AC and BC stimulation. The experimental procedure is complicated and requires extensive training of the test persons, though the setup is simple as shown in figure 4. Bárány [5] reports on the possibility of complete cancellation of hearing sensation, though it is obvious that this depends on many settings and factors. To reproduce his finding, which should be associated with a reduction of BM displacement, the OCW and stapes footplate were stimulated simultaneously by pressure.

The application of a realistic sound pressure level to the OCW was not easy because in experiments BC stimulation is done at a large distance from the OCW. Though the area of the OCW (A_{OCW} = 136.6 mm^2) to the area of the stapes footplate (A_{FP} = 5.5 mm^2) was approximately 25, the pressure ratio to obtain comparable BM displacements was only 4 at f = 2 kHz. Therefore, the OCW was stimulated by 58 dB SPL and the stapes footplate by 70 dB SPL at this frequency. The phase shift between the two pressure signals was 180°. The reduction of the maximum BM displacement from 2.15 pm with separate stimulation (AC or BC) to 0.8 pm with simultaneous stimulation is 8.56 dB (fig. 5).

With this comparably high frequency (2 kHz), the place of maximum displacement shifted to a more basal place on the BM compared to exclusive BC or AC stimulation. This was the result of the large phase shifts of the interfering AC and BC signals, which are relevant, especially at this frequency [2]. In case of f = 435 Hz, which is the frequency Bárány [5] used in his experiments, the reduction was 9.64 dB (4.22–1.39 pm). The complex pattern of BM displacement in case of the superposition of AC and BC stimulation is postponed to a future report.

Increase in BM Displacement after Footplate Removal with BC

During stapedectomy, the complete stapes footplate is removed. Similar to the superior semicircular canal dehiscence where BC sensitivity was increased for frequencies below 2 kHz [6], BM displacement increased by 9 dB at f = 1,500 Hz (fig. 6) in the finite element model. The increase was larger if the area of the opening increased as it is shown in figure 6. The smaller piston (diameter 0.6 mm) area of A = 0.28 mm^2 reduced the increase by up to 2 dB, depending on the frequency (fig. 6, piston open hole). Because BM displacement with a mobile elastic footplate does not differ considerably from the fixed state shown here, it is not presented in figure 6.

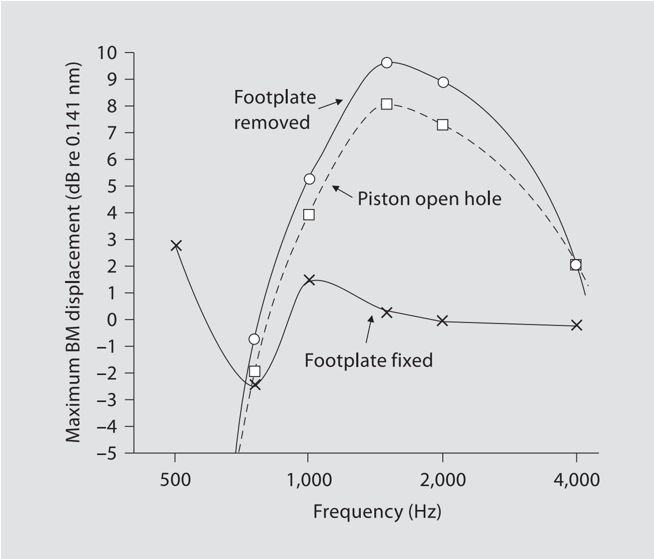

Fig. 6. The open footplate and the piston hole during stapedectomy increases the maximum BM displacement up to 9 dB in the finite element calculation. These results are similar to the increase in BC sensitivity below 2,000 Hz with the superior canal dehiscence syndrome [6].

The stimulation level of external pressure was 94 dB SPL in these cases. In BC measurements, the effective level at the cochlea can be lower and irregular along the cochlea wall because of anatomical conditions.

The physical interpretation of the increase in response can be the lowering of the acoustical impedance to fluid movements and therefore the increase in fluid movements and as a consequence the increase in BM displacement.

Discussion

The simulation of the wave propagation on the BM in the cochlea with BC excitation confirms early acoustical experiments and clinical findings. In this preliminary simulation, the bone was not directly taken into account. Instead, a homogeneous pressure application on the boundary walls of the cochlea was used.

In further steps of modelling the ear, parts of the temporal bone and particularly components of the middle ear will be included (three ossicles, two muscles, five tendons). This will enable us to study the influence of inertial BC, i.e. the contribution of the middle ear structures to BC, and the osseotympanic BC, i.e. sound energy transmitted from the external ear canal to the tympanic membrane, setting up an AC response [7]. In case of simulation of the otosclerotic ear with an immobile stapes footplate, it was permissible to use the cochlea model without the middle ear because in this case it does not matter if the ossicles are present or not.

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