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Three-dimensional Biomechanical Models for the Middle and Inner Ear

Introduction

The human peripheral auditory system is divided into the outer, middle and inner ear. The acoustic signal innervates the eardrum. The ossicles carry the signal forward to the inner ear. The system of the three ossicles transforms the acoustic signal. Another function of the middle ear is to protect the inner ear against loud noise. In the inner ear, the structure being responsible for hearing is the cochlea. It incorporates the organ of Corti containing the sensory cells that perform the transduction from mechanical excitation into auditory nerve signals. The cochlear can be described physically by three sections filled with fluid and separated by membranes. One of these is the basilar membrane. Acoustic stimulation by external sound is transformed into traveling waves with amplitude peaks at different places on the basilar membrane depending on the frequency of stimulation. An active mechanism including the outer hair cell somatic electro motility can add energy to the basilar membrane by providing positive feedback to the membrane vibrations. This phenomenon of cochlear amplification results in high sensitivity and increased frequency selectivity of the ear.

Material and Methods

Our long-term goal is to build three-dimensional passive and active biomechanical, physiologically based models of the human middle ear and the cochlea using different methods like Finite Element Methods (FEM) and visualize the motions resulting as responses to acoustic stimuli in animations. Such models allow testing hypotheses of cochlear function with applications in improving cochlear implants and hearing aids. The models can be tested and validated by comparison of their predictions with data like basilar membrane velocities, cochlear tuning curves, frequency responses and vibration patterns of the micromechanical structures, resulting from experiments mostly performed on animals. Measurements of these characteristics of the cochlea in vivo are very difficult, since the cochlea is vulnerable and the basilar membrane becomes a passive mechanical structure, as soon as the active cochlear mechanisms die out. In the latter case passive basilar membrane motion only will cause excitation of the inner hair cells generating action potentials in the auditory nerve fibers.

The ossicles are modeled on the basis of micro CT data with the finite element program ABAQUS. This allows determining the wave propagation through the ossicles. In further simulations the structure of the whole middle ear should receive attention. Parallel to the simulation of the middle ear the wave propagation in the Cochlea will be simulated. Here we start by modeling the passive mechanical mechanism of wave propagation. The active mechanisms of cochlear amplification, that are still poorly understood, will be added upon our passive models. The mechanics of the cochlea can be divided into micro-mechanical parts that refer to the internal mechanics of the organ of Corti, and macro-mechanics that refer to the mechanics of the cochlea as a whole. For each of them, models exist at different levels and dimensionality. A comprehensive model of the human cochlear must integrate the mechanical, electrical and acoustic phenomena (hydrodynamic modeling of fluid flows) in the cochlear. We start our work towards a three-dimensional model of the cochlear by reviewing the existing models e.g. [1] and their results.

Discussion

The first simulations show the problems of modeling the hearing process. It is very difficult to find the material parameters. In order to simulate the wave propagation in the middle ear it is also necessary to simulate the tendons and ligaments and furthermore the geometry of the bones and the cochlea has an influence on the wave propagation. An appropriate simulation model of wave propagation in the cochlea must consider the three-dimensional (viscous) fluid-basilar membrane interaction. Here a careful model must incorporate the curvature and the elastic shell structure of the basilar membrane implying the need to employ delicate concepts of differential geometry for the description of the boundary conditions of the partial differential equations involved in the modeling process.

The aforementioned combined sophisticated 3-d-models (going far beyond the current state of the art) are needed to obtain a realistic and detailed description of relevant mechanisms during the hearing process being necessary to develop improved hearing aids. An advanced model of the cochlea will e.g. be needed to understand the interaction of the cochlea with cochlea implant used in cases where parts of the cochlea remain functional. Furthermore a refined cochlea model will e.g. be needed to provide an improved distribution of medication in the cochlea.

References

[1] Givelberg E., Bunn J.: A comprehensive three-dimensional model of cochlea. Journal of Computational Physics : Vol. 191, Issue 2, p.377-391 , 2003.

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