A Three Dimensional Model of the Organ of Corti of the Guinea Pig

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Introduction

For the function of the inner ear the mechanical linkage of basilar membrane displacement to the deflection of the inner hair cell stereocilia is essential and investigated here. Besides the passive excitation by a pressure on the basilar membrane also the excitation by electromotile outer hair cells as well as by the hair bundles of the outer hair cells is studied. Based on geometrical data of the guinea pig and experimental velocity measurements the organ of Corti is modelled by means of the finite element method. The fluid and the structure are modelled as linear material with small displacements. The interaction of the fluid and the structure is implemented as a matrix coupling. The geometry is extracted from laser scanning microscope stacks and material properties are taken from the literature and adjusted to match experimental results. This model provides a helpful tool to understand experimental data more in detail. It is possible to look for the influence of geometrical variations and material properties. Different configurations and boundary conditions are modelled and the relation of excitation to inner hair cell stereocilia displacement due to bending is analysed.

Model

The geometry is for the guinea pig and based on literature [5, 7] and image stacks for the organ of Corti as presented in [1]. Here all values are adjusted for the third turn (c_f = 0.8 kHz). The cross-section is fully captured. In the longitudinal direction a half hair cell width is modelled with symmetry boundary conditions at the ends (figure 1).

The material properties are based on the model of Steele and Puria [9] and adjusted to match different experiments [2, 3, 6, 8, 10]. For experiments of single cells the neighboring material is replaced by fluid and the applied forces and displacements are introduced as boundary condition to represent the real experimental situation.

The outer hair cell walls are modelled by piezo material to reproduce the electromotile effect. The whole model uses a linear and passive material law for the fluid as well as for the structure. The fluid is implemented as user defined element into a structural finite element solver [4]. A matrix coupling strategy is used for the fluid with the structure in conjunction with a harmonic ansatz, thus the full system has to be solved just once for each frequency.

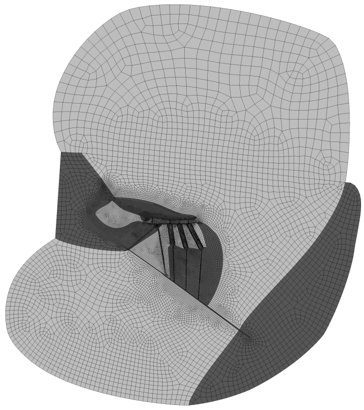

Figure 1: Finite element mesh of the organ of Corti embedded in the cochlea. Dark gray areas are solid materials and light gray fluid.

Computations

In the organ of Corti a mechanical displacement of the basilar membrane is transferred into a nerve signal. It is known on the one hand that the tip deflection of the inner hair cell stereocilia is important for this process and on the other hand that there are different possible mechanism to amplify the mechanical displacement of the basilar membrane. One is the electromotile outer hair cell and another the active hair bundle of the outer hair cells. Both introduce forces into the organ. Here the response of the organ to these two loads as well as a pressure load on the basilar membrane are investigated in respect to the deflection of the inner hair cell stereocilia. As the cuticular plate is moving as well, just the relative motion is analysed.

The geometry of the cells is subject to some variations and sensitive to the shrinking and swelling during the preparation, the geometry is not precisely known. As an example here it is assumed that the hensen stripe, which is located just next to the outer hair cell stereocilia changes in size. For the two configurations (small and large) all the computations for the three different load cases mentioned above are evaluated.

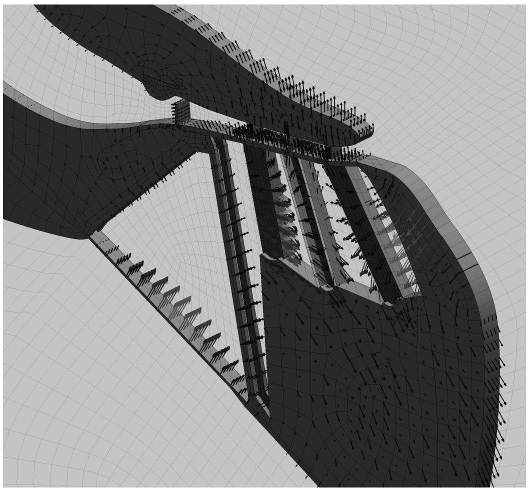

Figure 2: Displacement field of the structure in response to an electromotile excitation.

Table 1: Amplitude ratios of inner hair cell stereocilia deflection to excitation amplitude

Hensen stripe	basilar membrane	hair bundle	hair cells
small	0.04	0.11	0.25
large	0.46	1.51	0.38

Results

As an efficiency ratio here the deflection of the inner hair cell to the mean displacement at areas where the load is applied is taken. These amplitude ratios are given in table 1 for the three load cases: pressure on the basilar membrane, electric field on the outer hair cells and force of the hair bundle and two geometries with small and large hensen stripe. The hair bundle force is applied such that at the cilia tip there is a force pointing in radial direction towards lateral and at the bottom a force with same amplitude and direction but opposite orientation (towards inner sulcus).

The full displacement field is rather complex. As an example the vectors are plotted for some time instant for an electromotile excitation in figure 2. An important aspect is the transfer of excitation to stereocilia deflection of the inner hair cells. This deflection of the inner hair cell stereocilia tips is low for a pressure load. If the hensen stripe is increased in size, the fluid gap narrows and the pressure drop around increases for an electromotile response. By this also the acting force on the hair bundle of the inner hair cells increases and so the deflection. Besides this effects for a squeezing motion of the subtectorial space the hair bundle produces a shearing motion. Shearing of tectorial membrane in respect to the reticular lamina produces by the hensen stripe a fixed volume moving radially. This displaced volume has to be equalised by the incompressible viscous fluid and so produces a flow in the vicinity of the hair bundles.

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