Extended Abstract

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Fluid Pressure Distribution and Tonotopy in the Human Inner Ear

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The human inner ear or cochlea is a bone structure of spiral shape and is mainly composed of two conical chambers which are filled with fluid and separated by a soft membrane, the basilar membrane. Both chambers are connected through a small opening, called the helicotrema. At their base, the chambers are closed by the stapes footplate and the round window membrane. In case of a normal ear, sound is received by the eardrum, transmitted through the middle ear ossicles and finally excites the inner ear fluid through the vibration of the stapes footplate. According to present hearing theory, this leads to pressure waves in the cochlear fluid which in turn results in characteristic vibration behavior of the basilar membrane. Related to the sound frequency, hair cells in certain areas of the basilar membrane are stimulated and cause hearing nerve stimulation. Since the cochlea represents a closed hydraulic system with a complex geometry, the motion of the basilar membrane as well as the fluid pressure can hardly be measured. Therefore, a numerical model of the uncoiled cochlea is developed representing the fundamental physical effects occurring in the cochlea, taking the fluid-structure interactions into account. The transfer behavior of the cochlear system is investigated for different excitation frequencies within the auditory frequency range of humans. The simulations show the passive vibration of the basilar membrane resulting in the characteristic traveling wave. These results allow to study the mapping of the excitation frequency to its characteristic place along the basilar membrane, called tonotopy.

The geometry of the Finite Element model is based on anatomical data published in literature. The model consists of two straight, tapered chambers separated by the basilar membrane. The inner ear fluid properties are similar to a salt-water solution, thus the fluid is treated as slightly compressible. The cochlear structures include the round window membrane, the stapes footplate and the basilar membrane. The round window membrane and stapes footplate represent the boundaries to the middle ear. The stapes footplate is treated as a rigid body in order to apply the physiological amplitudes as kinematic boundary conditions. The round window membrane is located in the bottom wall at the basal end of the scala tympani and has a diameter of 1.8 mm. In the numerical model, this very compliant membrane is treated as an isotropic, elastic material. The thickness of the basilar membrane decreases from the basal end towards the apex, whereas its width increases [4]. This leads to a decreasing stiffness towards the apex along the basilar membrane length of 31 mm. From a morphologic point of view, the basilar membrane must be modelled with an anisotropic elastic material behavior. The material formulation used for the basilar membrane in this Finite Element model is based on the formulation for guinea pigs [1] with modified parameters. All solid structures in the Finite Element model are discretized by standard, quadratic solid elements.

The cochlea model is excited harmonically through the piston-like motion of the stapes footplate applying physiological amplitudes [3]. For an excitation frequency of 1 kHz the transversal amplitude of the basilar membrane relative to that of the stapes footplate is shown in Figure 1 for two discrete time points of a cycle. Due to the fluid viscosity and the structural damping, adjacent partitions of the basilar membrane vibrate with an increasing delay in phase from base towards the apex. The spatially moving oscillation nodes result in the characteristic passive traveling wave of the basilar membrane. Thereby, the amplitude increases from the base towards the apex reaching a maximum amplitude at a characteristic point along the cochlea indicated by the envelope in Figure 1. Beyond this point, the amplitude decreases rapidly and the apical domain of the basilar membrane remains at rest.

The basilar membrane amplitudes for excitation frequencies of 0.25, 0.5, 1, 2, 4 and 8 kHz are shown in Figure 2 (left). The global maximum amplitude occurs for an excitation frequency of 1 kHz. As the amplitudes are plotted relative to that of the stapes footplate, the gain of the cochlear system obviously has a maximum around 1 kHz. This result is consistent with the transfer behavior of the middle ear, indicating a maximum amplification in the same frequency range [3]. For an increasing excitation frequency, the maximum amplitude is shifted towards the base of the cochlea. This behavior leads to a unique mapping of each excitation frequency to a distinct loca-

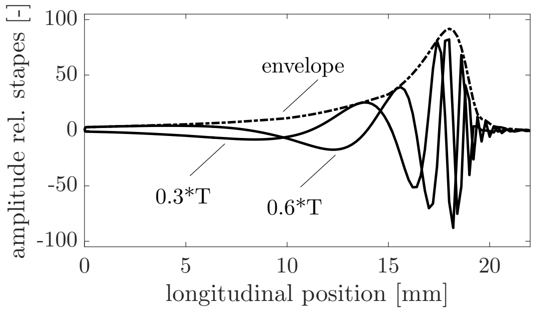

Fig. 1: Transversal amplitude of the basilar membrane relative to that of the stapes footplate for two different points of time of a cycle for an excitation frequency of 1 kHz

tion along the basilar membrane and is called tonotopy. Apparently, the cochlear system acts similar to a discrete frequency analyzer.

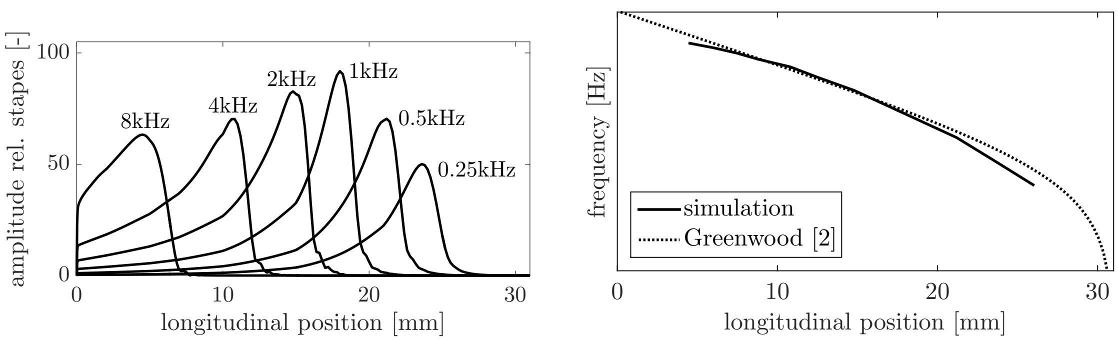

Fig. 2: Envelopes of the basilar membrane vibration (left) and calculated tonotopy in comparison with experimental data (right)

The position where the maximum amplitude of the traveling wave occurs is shown along the excitation frequency in Figure 2 (right). For frequencies above 0.5 kHz the maxima are distributed almost logarithmically along the length of the basilar membrane. For lower frequencies the distance between the maxima decreases and the tonotopy deviates from the purely logarithmic distribution. The calculated tonotopy is in range with the experimental result from literature, which is based on the correlation with critical bandwidths gained from psychoacoustic experiments [2]. Also, the fluid pressure distributions are evaluated to investigate the interaction between fluid pressure and motion of the basilar membrane. These results provide a deeper understanding of the formation of the characteristic vibration of the basilar membrane.

References

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