Passive Traveling Wave, Tonotopy, and Fluid Pressure Distribution in the Human Inner Ear

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Abstract

The inner ear or cochlea is composed of mainly two conical chambers which are filled with fluid and separated by a soft membrane, the basilar membrane. The closed hydraulic system is excited through the vibration of the stapes. This leads to pressure waves in the cochlear fluid which in turn results in the 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. In order to predict and understand the effect of inner ear diseases on hearing impression as well as to develop new hearing implants, a deeper understanding of the cochlear dynamics is needed. For this purpose, a Finite Element model of the human cochlea is developed including the relevant fluid-structure interactions. Solving the system in the frequency domain, the characteristic traveling wave of the basilar membrane is calculated. It can be shown that the position of the maximum amplitude of the basilar membrane depends on the excitation frequency and the maximum amplification occurs around 1 kHz. Additionally, the frequency distribution along the length of the basilar membrane is investigated and compared to experimental results.

Keywords: Biomechanics, Cochlea, Fluid-Structure Interaction, Passive Traveling Wave, Tonotopy, Fluid Pressure Distribution

1. Introduction

The human inner ear or cochlea is a bone structure of spiral shape and is composed of mainly two conical chambers which are filled with fluid and separated by a soft membrane, the basilar membrane. At the apical end, both chambers are connected through a small opening, called the helicotrema. At the base, the chambers are closed by the stapes footplate and the round window membrane. The cochlea can, therefore, be considered as a closed hydraulic system. 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. In order to predict the effect of pathological changes due to inner ear diseases on the cochlear dynamics and thus on hearing impression as well as to develop new active and passive hearing implants, a deeper understanding of the cochlear system is needed. However, 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, in this study 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 it's characteristic place along the basilar membrane, called tonotopy. In a next step, the corresponding spatial fluid pressure distribution along the cochlear chambers is evaluated and allows new insight into the cochlear physics.

2. Geometry, Material and Methods

The geometry of the Finite Element model is based on anatomical data published in literature. The model consists of two straight, tapered chambers. The lower chamber, scala tympani, is separated by the upper chamber, scala vestibuli, through the basilar membrane. At the basal end, the scala vestibuli is connected to the vestibulum. At the apex, both chambers are connected through the helicotrema. The vestibulum, scala vestibuli and scala tympani are filled with inner ear fluid and add up to an enclosed fluid volume of 105 mm^3. The fluid properties are similar to a salt-water solution, thus the fluid is treated as slightly compressible. Since the cochlear fluid dynamics is characterized by a Reynolds number well below one, the viscous effects have to be captured by the fluid formulation. Since standard acoustic elements neglect the velocity field in the fluid and thus are not capable to capture the viscous effects in the boundary layers, these are not appropriate to describe the cochlear fluid dynamics. Since the amplitudes of the cochlear structures are small, nonlinearities which have to be taken into account in most engineering flow problems can be ignored and only the linear problem is solved here. The convective terms are neglected, but as the frequencies are high, the inertial term is retained. Further, the velocity in the fluid equations is replaced by the time derivative of the displacement. In this way, the fluid formulation is convenient for coupling with the cochlear structures. The approach allows an efficient computation of the linear and strongly coupled fluid-structure interaction problem in the frequency domain.
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 located in the upper wall of the vestibulum and has an elliptic shape with an area of 3 mm^2. It 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 it's 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 can be partitioned transversally into the arcuate and pectinate zone [1]. Since in the latter zone the filaments are grouped into fibers and are embedded in a ground substance, an anisotropic elastic material behavior is used for the pectinate zone. However, the arcuate zone is treated as an isotropic elastic material. 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.

3. Results

The cochlear 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.

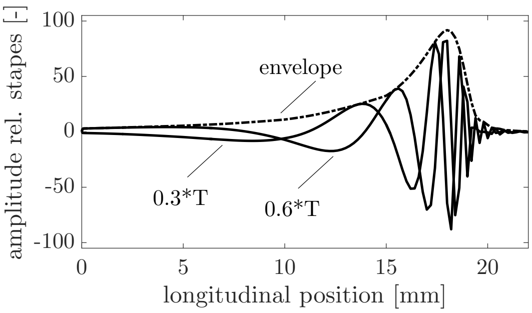

Figure 1: Transversal amplitude of the basilar membrane relative to that of the stapes footplate for two different points of time of a cycle for an excitation frequency of 1 kHz.

The basilar membrane amplitudes for excitation frequencies of 0.25, 0.5, 1, 2, 4 and 8 kHz are shown in Figure 2. 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 it's 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 location along the basilar membrane and is called tonotopy. In this way, the cochlear system acts similar to a discrete frequency analyzer.

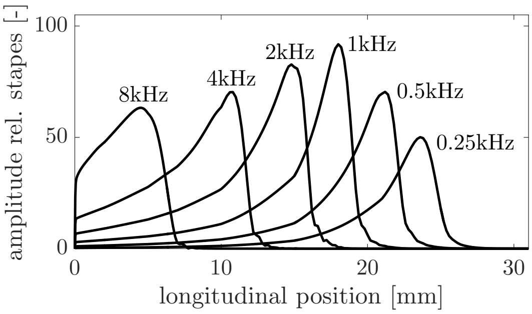

Figure 2: Envelopes of the basilar membrane vibration for different excitation frequencies.

The position, where the maximum amplitude of the traveling wave occurs is shown along the excitation frequency in Figure 3. It becomes apparent, that 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].

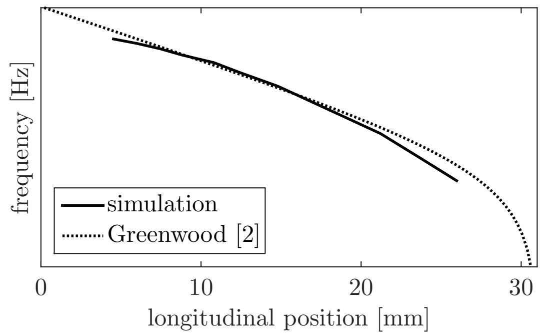

Figure 3: Calculated tonotopy in comparison with experimental data from literature [2]

In a next step, 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.

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