Feed-forward/Feed-backward Mechanical Amplification in the Mouse Cochlea

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Abstract

Introduction
Sound vibrations are collected from the external environment by the eardrum and are guided to the basilar membrane in the cochlea. Pressure differences in the two scalae of the cochlea result in a traveling wave on the basilar membrane (figure 1). The tiny displacements are detected by the deflection of thousands of hair cells, situated along this membrane. It is hypothesized that some 3/4 of these hair cells, the outer hair cells, work as microscopic energy pumping motors, resulting in amplification of the basilar membrane motion (Brownell et al. 1985). It still remains to be understood how thousands of these outer hair cells work together, resulting in the high sensitivity and frequency selectivity of mammalian ears. Here we present our first modeling results using COMSOL Multiphysics®.

Use of COMSOL Multiphysics®
A 3D box model, based on the geometry of the unrolled mouse cochlea has been developed (figure 1). First step is a passive model, without the active stimulation of the outer hair cells. In this model, linearized Navier-stokes equations (Acoustics Module) for the fluid in the scalae, coupled with a structural orthotropic material for the basilar membrane are solved in the frequency domain.

In a second step, we introduce the motility of the hair cells. The feed-forward and feed-backward mechanism, proposed by Yoon et al. (2011) (see figure 2), results in the following continuous edge force (F_BM) in the center of the basilar membrane (with F_shear(x), the shear force of stereocilia at position x; a1 and a2 are amplification gain factors a1 = a2 = 0.12; Dx1 = 1.3 um, Dx2 = 32 um):
F_BM (x) = a1 F_shear (x-Dx1) - a2 F_shear (x+Dx2)

Results
The BM velocity at the peak in the passive model (figure 3, blue) is 70 times larger than the input (stapes velocity). The peak in the active model (figure 3, red) is 250 times the input, shifted to higher frequencies and sharper than the passive results. Compared to the results of Yoon et al. for the human, cat, chinchilla and gerbil, similar results for the magnitude and phase were obtained, except for the lower amplification in the active model.

Conclusion and future direction

Computer models are a helpful framework to understand the active mechanisms of the basilar membrane. Recently, Yoon et al (2011) proposed a feed-forward and a feed-backward mechanism for the outer hair cells. They used the WKB approximation and a feed-forward and feed-backward approximation (see figure 2). Here we used COMSOL Multiphysics® to build a similar model for mouse. Our results show good agreement with their WKB approximation and with experiments. The advantage of using a numerical technique over the WKB technique is the possibility to add more detail about the micro-structure of the hair cells and supporting cells. As such, we hope to explain how a backward traveling wave, known in clinics as the oto-acoustic emission (Kemp 1978), is generated by the outer hair cells.

Reference

Brownell W.E., Bader C.R., Bertrand D., de Ribaupierre Y, mechanical responses of isolated cochlear outer hair cells, Science 227 (194-196), 1985

Yoon Y-J, Steele C.R., Puria S., Feed-Forward and Feed-Backward Amplification Model from Cochlear Cytoarchitecture: An Interspecies Comparison, Biophy J 100 (1-10), 2011

Kemp D. T., Stimulated acoustic emissions from within the human auditory system, J. Acoust Soc Am 64 (1386-91), 1978

Figures used in the abstract

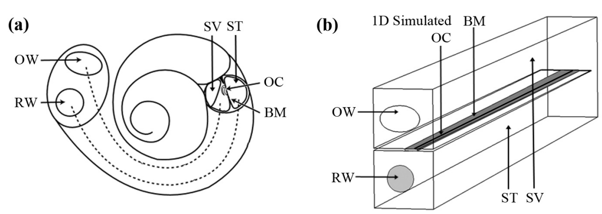

Figure 1: (a) sketch of cochlea and (b) simple box model in COMSOL. The middle ear input is simulated with a pressure on the oval window (OW), resulting in a pressure wave in the scala vestibule (SV) and scala tympani (ST) and a displacement of the basilar membrane (BM, results see figure 3) and round window (RW). The organ of Corti (OC) contains the outer hair cells, here simulated as an edge force on the BM

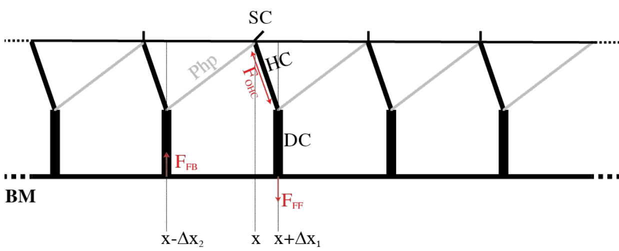

Figure 2: Principle of feed-forward and feed-backward amplification mechanism: A shear of the stereocilia (SC) at position x, results in an expanding hair cell which will give a forward (x+Dx1) push via the Deiter cell (DC) and a backward (x-Dx2) pull via the phalangeal process (Php) on the basilar membrane (BM).

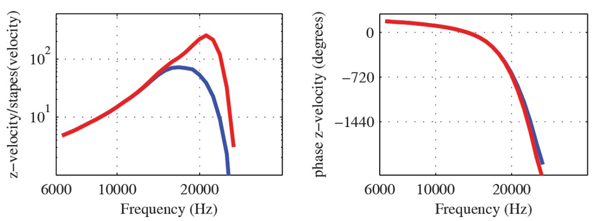

Figure 3: Magnitude and phase, at 1 position for different frequencies, of perpendicular basilar membrane velocity, for passive model (blue) and active model (red).