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

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1. Introduction

Sound vibrations are collected from the external environment by the eardrum and 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 (fig1). The tiny displacements are detected by the deflection of thousands of hair cells, situated along this membrane. It is hypothesized that some ¾ 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.

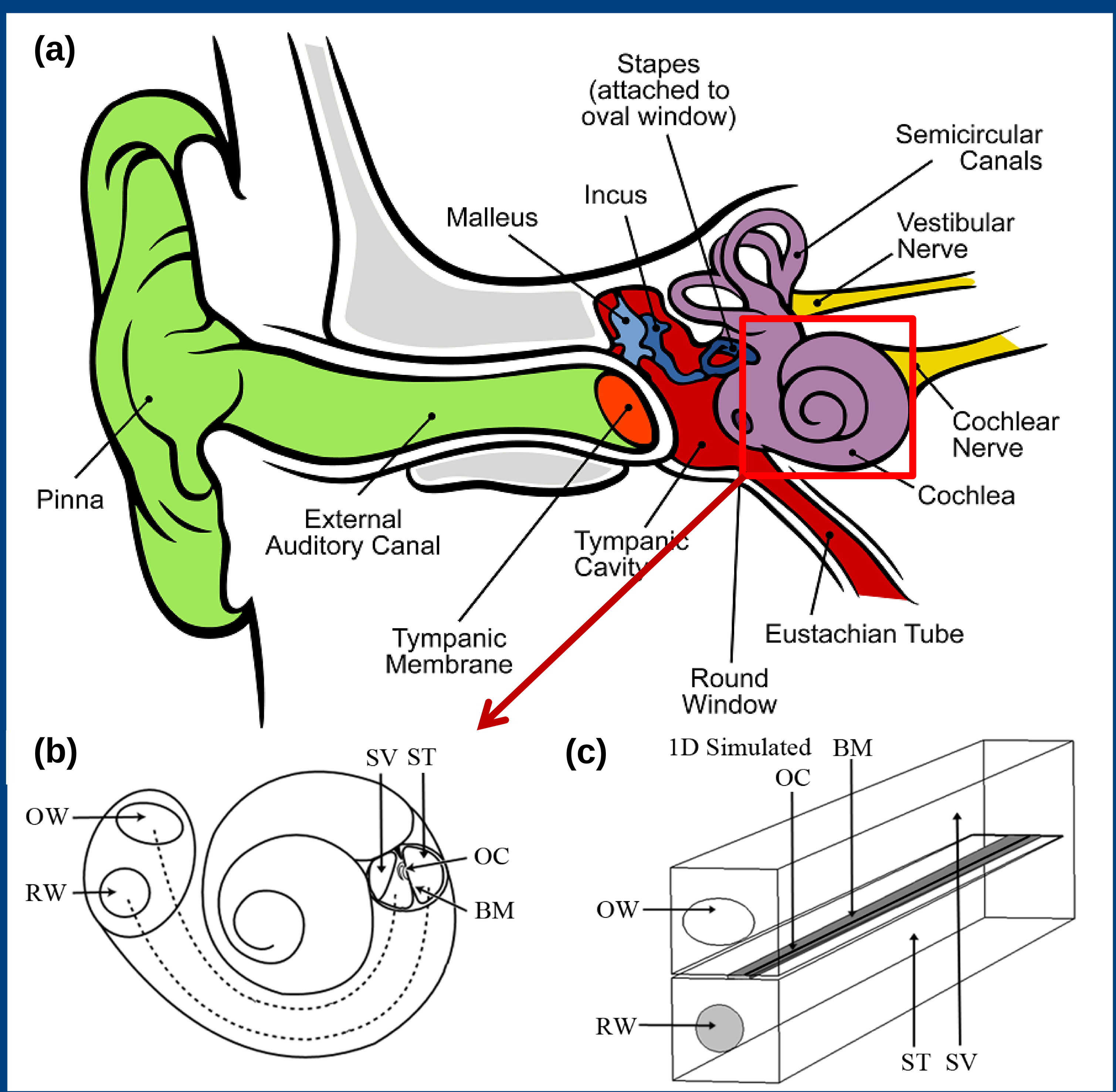

Fig. 1: (a) Overview of the human ear, cochlea highlighted in red square (b) sketch of cochlea and (c) simple box model in COMSOL. The middle ear input is simulated with a pressure on the oval window (OW), resulting in a pressure wave in the scala vestibule (SV) and scala tympani (ST) and a displacement of the basilar membrane (BM, results see fig3) and round window (RW). The organ of Corti (OC) contains the outer hair cells, here simulated as an edge force on the BM.

2. Use of COMSOL Multiphysics

1) A 3D box model, based on the geometry of the unrolled mouse cochlea has been developed (fig1). First step is a passive model, without the active stimulation of the outer hair cells. In this model linearized Navier-stokes equations (thermo-acoustic module) for the fluid in the scalae, coupled with a structural orthotropic material for the basilar membrane are solved in the frequency domain.

2) The motility of the hair cells is introduced. Feed-forward and feed-backward mechanism, proposed by Yoon et al. (2011) (fig2), 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; α_1 and α_2 are amplification gain factors; Δx_1= 1.3 µm, Δx_2= 32 µm; $\alpha_1 = \alpha_2$= 0.12):

$$F_{BM}(x) = \alpha_1\, F_{shear}(x - \Delta x_1) - \alpha_2\, F_{shear}\,(x + \Delta x_2)$$

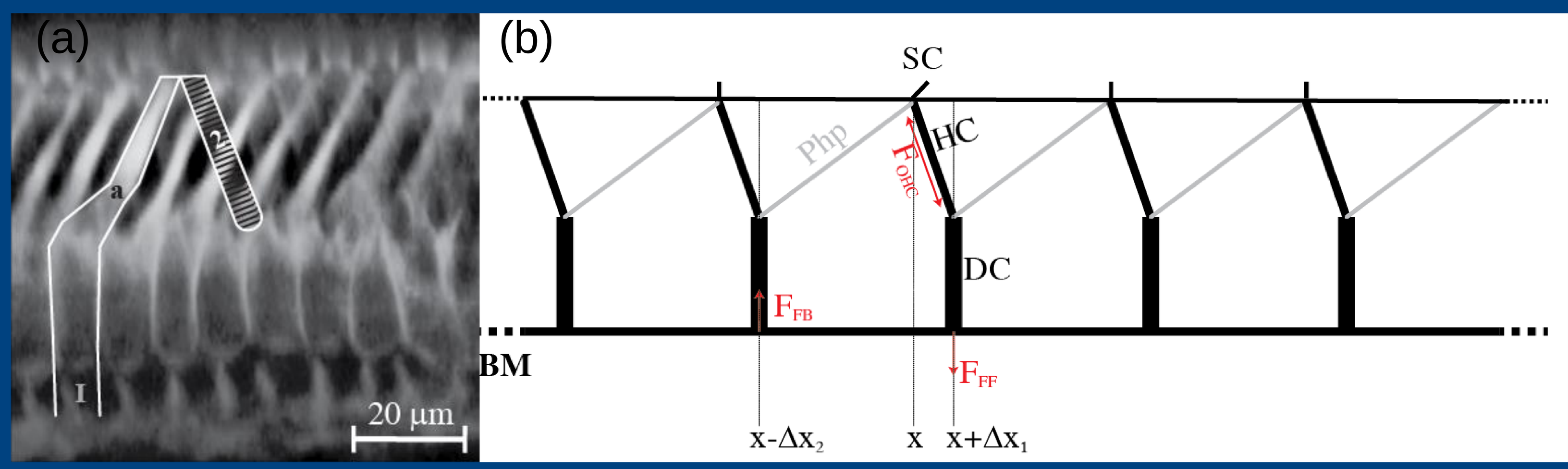

Fig. 2: (a) 2 photon microscope image of longitudinal arrangement of outer hair cell (HC,2) Deiter cell (DC, l) and phalangeal process (Php,a); (b) Principle of feed-forward and feed-backward amplification mechanism: A shear of the stereocilia (SC) at position x, results in an expanding HC which will give a forward (x+Δx_1) push via the DC and a backward (x-Δx_2) pull via the Php on the basilar membrane (BM).

3. Results

The BM velocity at the peak in the passive model (fig3, blue) is 70 times larger than the input (stapes velocity). The peak in the active model (fig3, 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 a lower amplification in the active model.

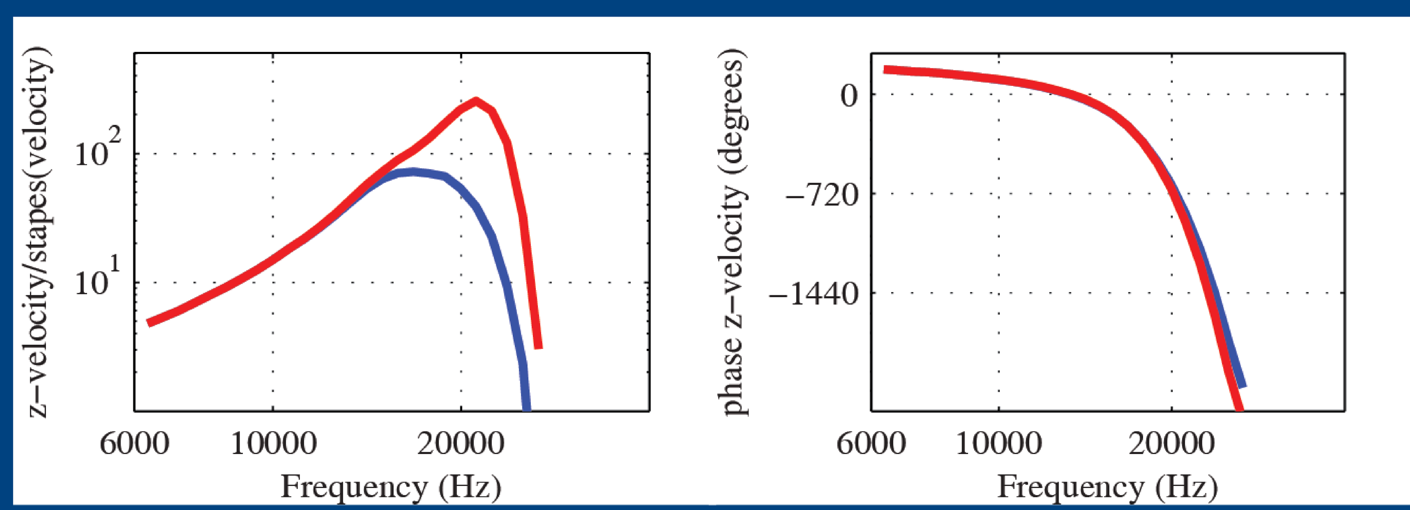

Fig. 3: Magnitude and phase, at 1 position for different frequencies, of perpendicular basilar membrane velocity, for passive model (blue) and active model (red).

4. 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 (fig2). Here we used COMSOL 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 (fig4). 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.

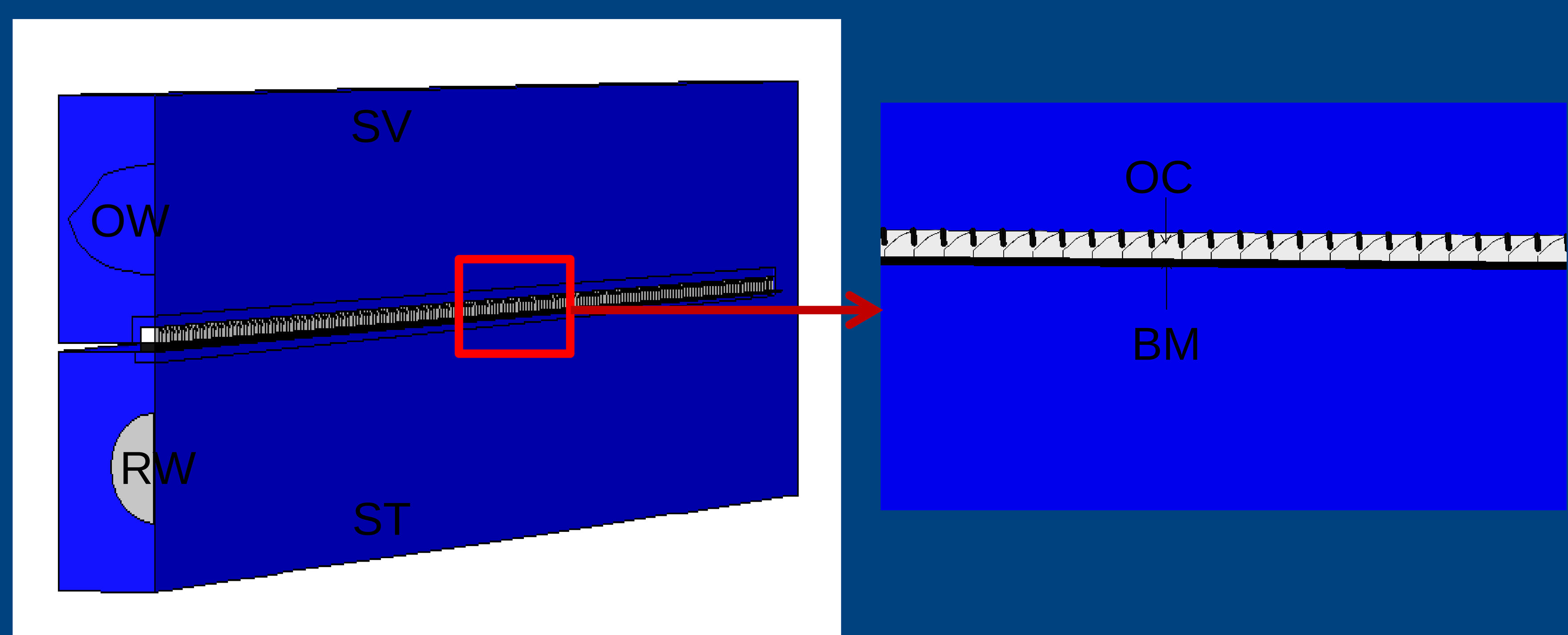

Fig. 4: Preliminary model: Organ of Corti (OC) is now simulated in an explicit way by using a macroscopic 'jelly' OC representation coupled with microscopic beam elements. Shear force on the stereocilia will now results in an expansion of the outer hair cells.

5. References

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