

INVESTIGATION ON INFLUENCE OF OUTER HAIR CELLS ON COCHLEA SLOW WAVE

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Abstract: This study focuses on the influence of the outer hair cells (OHCs) on the waves that propagate on the basilar membrane (BM). The human auditory system relies on the intricate organization of inner and outer hair cells within the cochlea. Inner hair cells serve as primary sensory cells, while the OHCs amplify signals. The activation of these hair cells is driven by the vibration of the BM and the overlying tectorial membrane. The spatial arrangement of hair cells along the cochlea enables frequency-specific responses, allowing the auditory system to process a wide range of sound frequencies. In this study, modal analysis is employed to explore the influence of the OHCs on the BM waves. The analysis model includes the BM and OHCs, with a comparison to a model excluding the OHCs. The frequency characteristics of propagation constants are compared between the two cases, shedding light on the structural dependence of propagation constants in the presence and absence of the OHCs.

Keywords: Cochlea, outer hair cell, basilar membrane, modal analysis, propagation characteristics

1. INTRODUCTION

The human auditory system contains tens of thousands of hair cells arranged in a single row of inner hair cells and three rows of outer hair cells (OHCs). The inner hair cells serve as the primary sensory cells and play a crucial role in our ability to perceive sound. On the other hand, the OHCs have an important function in amplifying signals. [1]. These hair cells are activated by the vibration of the basilar membrane (BM), a structure on which they rest. The tectorial membrane is located above the hair cells. The OHCs are directly connected to the tectorial membrane through their hair bundles. Stimulation of the OHCs occurs as a result of the shear forces generated between the vibrating BM and the overlying tectorial membrane. Due to the properties of the BM, traveling waves of different frequencies reach their peak amplitudes at different locations along its length. As a result, specific frequencies excite specific subsets of hair cells. Hair cells located at the base of the cochlea respond predominantly to high-frequency sounds, while those located at the apex exhibit greater sensitivity to low-frequency stimuli. Overall, the intricate organization and interactions between these different types of

hair cells, as well as their relationship to the basilar and tectorial membranes, allow our auditory system to effectively process and perceive a wide range of sound frequencies.

A significant volume of research has been dedicated to examining outer hair cells and their functions [2–8]. Fettiplace et al. discussed the remarkable speed and sensitivity with which cochlear hair cells respond to sound vibrations, experiencing submicron deflections of their hair bundle [2]. They highlighted that outer hair cells not only serve as detectors but also generate force to enhance auditory sensitivity and frequency selectivity. Describing recently identified proteins involved in the sensory and motor functions of auditory hair cells, they presented evidence supporting both cell body contractions and active motion of the hair bundle as mechanisms for force production. They suggested that both motor mechanisms are likely necessary to achieve the high sensitivity and frequency discrimination observed in the mammalian cochlea. Furness et al. investigated the structure and dimensions of rootlets in the sensory bundle of cochlear hair cells, focusing on their role in bundle stiffness and durability during mechanical stimulation [3].

Through microscopy and immunolabeling techniques, they discovered that the rootlets have a thick central core, widen at the ankle, and are embedded in a meshwork within the cuticular plate. They suggested that these rootlets strengthen the ankle region for enhanced durability and may interact with the lateral wall, anchoring the stereocilia and facilitating interactions between the bundle and the lateral wall. Aranyosi et al. investigated the motion of freestanding hair bundles as a function of frequency and bundle height [4]. The motions were measured from images obtained by strobing a light source at the corresponding frequency. They observed comparable movements of the tips and bases of the hair bundles, with a phase difference increasing by 180° as the frequency increased. Ciganović et al. investigated the mechanism by which the cochlea amplifies weak sounds and transmits them to the inner hair cells [5]. Through a combination of modeling and experimental measurements, they revealed how length changes in the outer hair cells affect the motion of the organ of Corti and finely tune the signal for transmission to the inner hair cells. They suggested that this mechanism may contribute to frequency discrimination and selective auditory attention in low-frequency perception.

In this study, we explore the impact of the OHCs on the BM waves through modal analysis. The analytical model comprises the BM, tectorial membrane, and OHCs. Additionally, we employ the analytical model excluding the OHCs. Subsequently, we compare the frequency characteristics of the propagation constants in both cases. Furthermore, we delve into the variations in the structural dependence of the propagation constants between the two scenarios.

2. MATERIALS AND METHODS

The organ of Corti is sandwiched between the BM and the tectorial membrane and includes three rows of OHCs. This study focused on the influence of the OHCs on the propagation characteristics of the wave propagating on the BM and used an analysis model that includes the OHCs, as well as the BM and the tectorial membrane, as shown in Fig.1. Comsol Multiphysics, based on the finite element

method, was used to investigate the phase and attenuation constants of the BM waves using modal analysis.

Each OHC is supported by Deiters cell and has stereocilia on top of it. The Deiters' cells are located on the BM, and the stereocilia are attached on the overlying tectorial membrane.

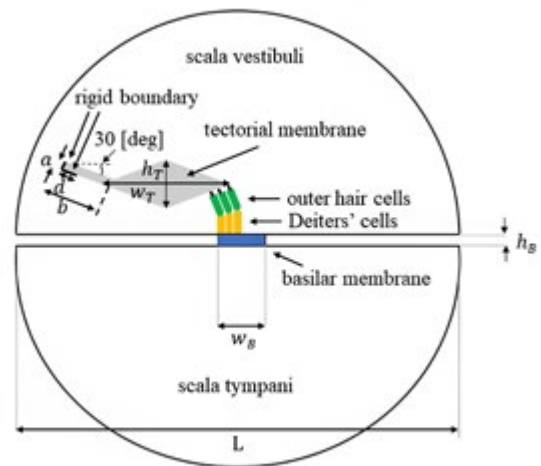


Fig. 1: Analysis model

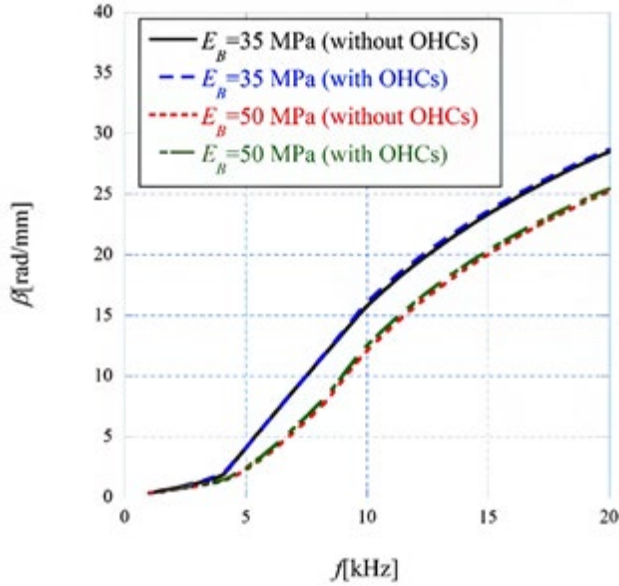
The Young's modulus of both the OHC and the Deiters' cell is 3 kPa, and that of the stereocilia is 100 kPa [9]. The parameters of the tectorial membrane are fixed: the width $w_T=150 \mu\text{m}$, thickness $h_T=50 \mu\text{m}$, and Young's modulus $E_T=3 \text{ kPa}$ [10]. The limbal attachment zone of the tectorial membrane and the spiral limbus are firmly fastened, and we modeled it as a rigid boundary ($d=30 \mu\text{m}$, $a=10 \mu\text{m}$, and $b=50 \mu\text{m}$). We used the width w_B , thickness h_B , and Young's modulus E_B of the BM as parameters. The radius of the chamber is fixed at $r=0.5 \text{ mm}$. Both the BM and the tectorial membrane have Poisson's ratio of 0.49 and a density of $1.2 \times 10^3 \text{ kg/m}^3$ [11, 12]. The fluid has a bulk modulus of $2.2 \times 10^9 \text{ Pa}$, a density of $1.034 \times 10^3 \text{ kg/m}^3$, and a viscosity of $2.8 \times 10^{-3} \text{ Pa}\cdot\text{s}$ [11, 12].

3. RESULTS AND DISCUSSION

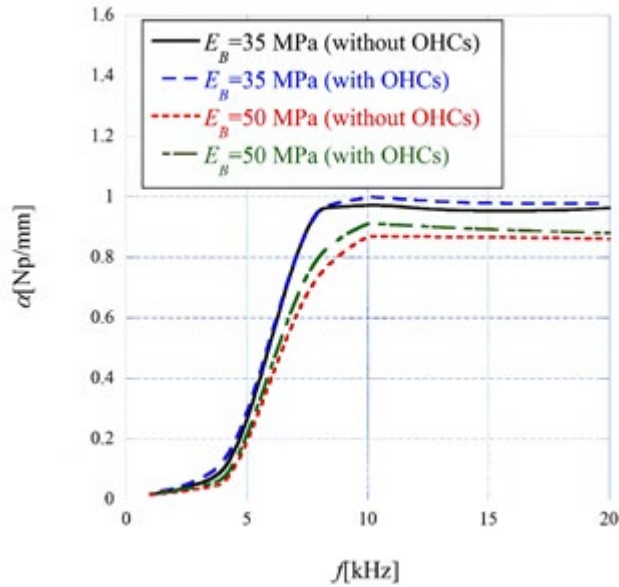
All results were obtained through modal analysis using COMSOL Multiphysics, based on the finite-element method.

Fig. 2 illustrates the frequency characteristics of the BM wave propagation constants. The

results are also presented for the scenario in which the OHCs are excluded from the analysis model. In Fig. 2(a), it is evident that



(a)

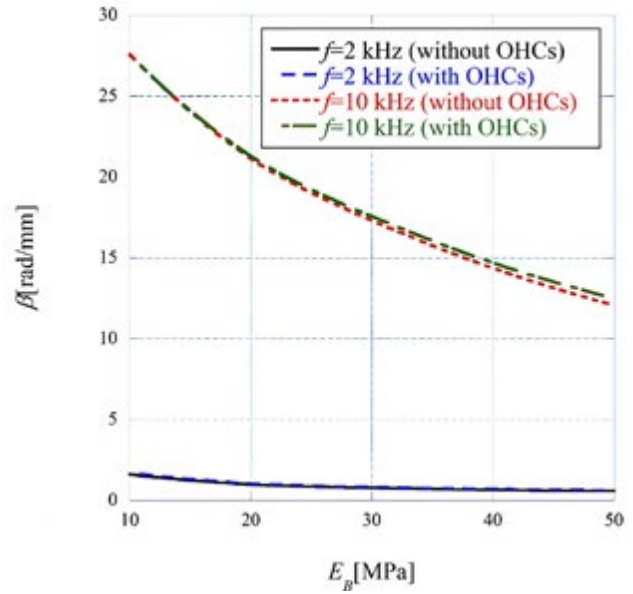


(b)

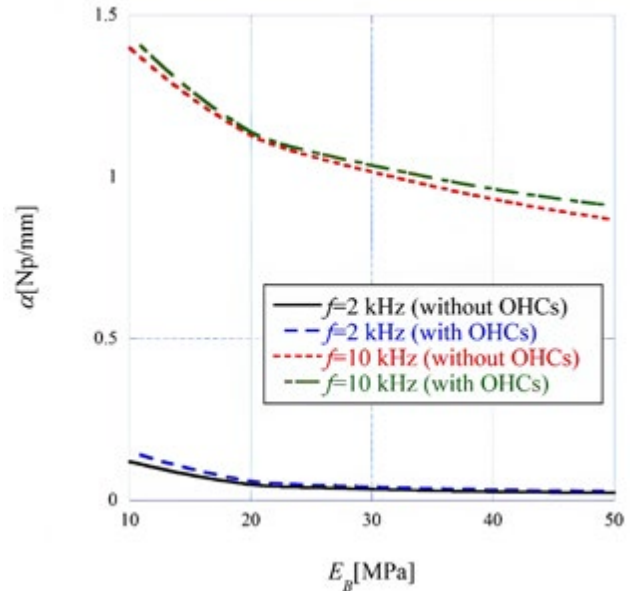
Fig. 2: Frequency characteristics of (a) phase constant and (b) attenuation constant of BM wave

OHCs have a minimal impact on the phase constants of the BM wave across a wide frequency range. However, as shown in Fig. 2(b), the inclusion of OHCs leads to an increase in the attenuation constants of the BM wave.

The influence of the OHCs becomes more pronounced at higher frequencies.



(a)



(b)

Fig. 3: (a) Phase constant and (b) attenuation constant as a function of Young's modulus of basilar membrane E_B

The phase and attenuation constants of the BM wave, dependent on the Young's modulus (E_B) of the BM, are depicted in Fig. 3(a) and (b), respectively. The acoustic frequencies chosen for this analysis are $f = 2$ kHz and 10

kHz. In Fig. 3(a), it is observed that OHCs have a minimal impact on the phase constants at low frequencies ($f = 2$ kHz). However, at high frequencies ($f = 10$ kHz), although the effect is small initially, it becomes more pronounced as the Young's modulus of the basilar membrane increases. Fig. 3(b) illustrates that the inclusion of OHCs results in an increase in attenuation constants, with the influence becoming significant at high frequencies. In contrast to the impact on phase constants, OHCs affect attenuation constants regardless of the frequency when the Young's modulus of the basilar membrane is low.

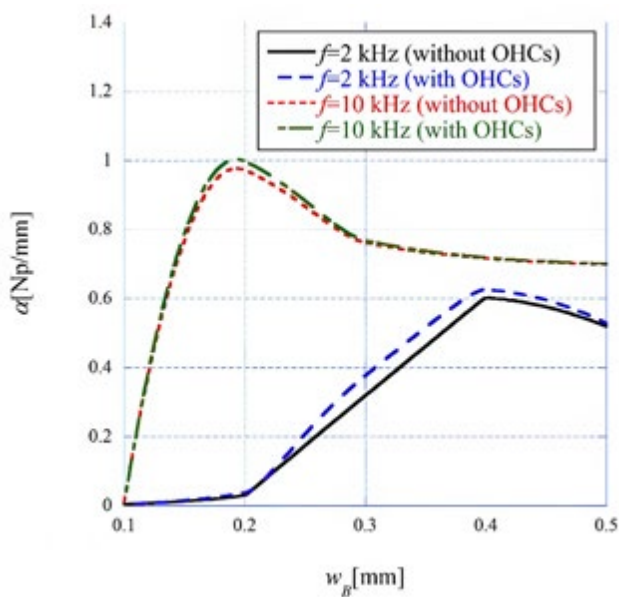


Fig. 4: Attenuation constant as a function of width of basilar membrane w_B

Figs. 4 and 5 present the attenuation constants of the BM wave concerning the width (w_B) and height (h_B) of the BM, respectively, at frequencies $f = 2$ and 10 kHz. In Fig. 4, it is evident that the influence of OHCs becomes significant when w_B is in the range of 0.3 to 0.5 mm for low frequency ($f = 2$ kHz). Conversely, the influence becomes pronounced when w_B is approximately 0.2 mm for high frequency ($f = 10$ kHz). Notably, the impact of OHCs varies depending on the wavelength. As depicted in Fig. 5, at $f = 10$ kHz, OHCs influence the attenuation constants irrespective of the height of the basilar membrane, while their impact is minimal at low frequency ($f = 2$ kHz). Given that the height of the BM is much smaller than the width, the dependence on h_B is hardly noticeable for low frequency ($f = 2$ kHz).

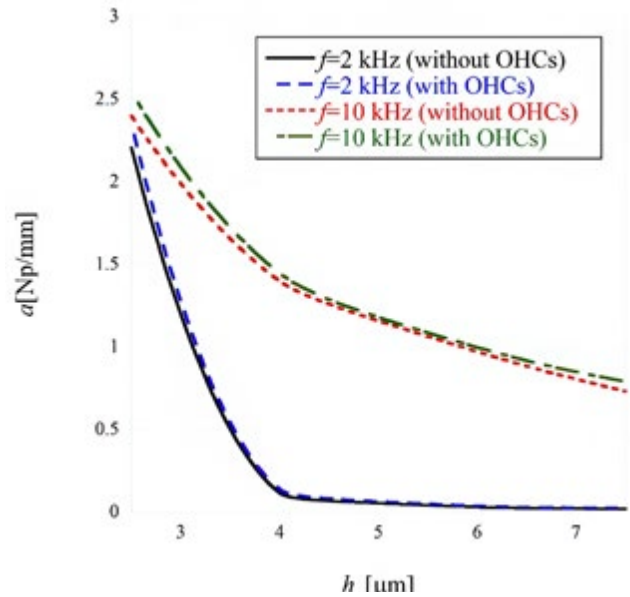


Fig. 5: Attenuation constant as a function of height of basilar membrane h_B

4. CONCLUSION

This study investigated the influence of OHCs on the propagation characteristics of waves on the BM within the organ of Corti. The analysis model incorporated the OHCs, the BM, and the tectorial membrane. The frequency characteristics of the BM wave propagation constants were examined, revealing that the OHCs have a minimal impact on the phase constants across a wide frequency range but lead to an increase in the attenuation constants, particularly at higher frequencies. The study further explored the dependency of phase and attenuation constants on the Young's modulus of the BM, showing that the OHCs exhibit a more pronounced effect at higher frequencies. Additionally, the research investigated how the width and height of the BM influence the attenuation constants. It was observed that the impact of the OHCs on attenuation becomes significant at specific ranges of the BM width for both low and high frequencies. Moreover, at high frequencies, the OHCs influence attenuation constants irrespective of the height of the BM, while their impact is minimal at low frequencies. This study contributes valuable insights into the role of the OHCs in shaping the propagation characteristics of BM waves, particularly highlighting their influence on attenuation constants at higher frequencies and their dependence on the BM width and height.

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