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ATTENUATION CHARACTERISTICS OF TECTORIAL MEMBRANE WAVE

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Abstract*: This study focuses on the attenuation characteristics of the waves that propagate on the tectorial membrane (tectorial membrane waves). The traveling wave on the basilar membrane (basilar membrane wave) plays a main role in transmitting acoustic signals. However, slow waves can propagate on the tectorial membrane other than the basilar membrane. If the tectorial membrane waves also progress along the cochlea from the base to the apex, they could have influence on the signal that is transmitted by the basilar membrane wave. We discuss the difference of the propagation characteristics between two types of the tectorial membrane waves and the basilar membrane wave by comparing the attenuation constants. First, we showed the difference of the displacement of the basilar and tectorial membranes between these waves. Then, we investigated their propagation characteristics including the phase constants and attenuation constants. Finally, we studied the structural dependence of the attenuation constants of the tectorial membrane waves.*

Keywords: *Tectorial membrane, basilar membrane, propagation characteristics, attenuation constants, slow wave*

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1. INTRODUCTION

The slow wave that propagates on the basilar membrane (BM) has been investigated by many authors [1–6]. It propagates from the base to the apex, and the displacement of the BM has a peak at a specific region along the cochlea depending on the acoustic frequency because the BM is graded in mass and stiffness along its length. The high frequency signal peaks near the base and the peak appears at the inner region toward the apex as the frequency becomes lower. On the other hand, the cochlea has the tectorial membrane (TM) which is incorporated in the organ of Corti between the BM and Reissner's membrane (RM) and slow waves can propagate on the TM [7]. Recent studies have shown that the wave motion of the TM may play an important role in determining the frequency selectivity in the hearing system [8–14]. Ghaffari et al. have shown that the TM supports traveling waves that are an inherent property of the structure with viscosity and elasticity. They have also computed the shear storage modulus and viscosity of the TM from the wave propagation velocity and shown that the basal segments are stiffer than the apical ones. Their results show the presence of the TM traveling wave that can couple a longitudinal extent of the cochlea and may interact with the BM wave to enhance sensitivity and tuning [8]. Meaud et al. have investigated BM and TM longitudinal coupling in order to determine the influence of the coupling on the tuning of the BM. They have asserted that the BM response to acoustic stimulus shows that the characteristic frequency is controlled by a TM radial resonance and that the effect of the TM longitudinal coupling is more significant than the BM longitudinal coupling [9]. Gummer et al. have measured the vibration of the TM by using the method of combining laser interferometry with a photodiode technique and shown that the resonant frequency of the TM is 0.5 octave below the one of the BM and the TM is polarized parallel to the reticular lamina. They have concluded that the TM resonant movement is due to a parallel resonance between the TM mass and the stereocilia of the outer hair cells [10].

In this study, we focus on the attenuation characteristics of the TM traveling waves. When the cochlea is stimulated by environmental sounds, the BM traveling wave occurs and plays a main role in transmitting acoustic signals. However, slow waves can propagate on the TM other than the BM. If the TM waves also progress along the cochlea from the base to the apex, they could have influence on the signal that is transmitted by the BM wave. If the attenuation of the TM waves is sufficiently bigger than the BM wave, the influence by the TM waves can be estimated to be small. We discuss the effect of the TM waves by comparing the attenuation constants between the TM and BM waves.

2. MATERIALS AND METHODS

Cochlea has the BM and RM. They divide it into three chambers; the scala vestibuli, scala media, and scala tympani. The TM is located in the organ of Corti between the BM and RM. This study focused on the difference of the attenuation constants between the TM and BM waves and used the analysis model that did not include the RM as shown in Fig. 1. Modal analysis was used to investigate the phase and attenuation constants of the TM and BM waves. Here, we used Comsol Multiphysics based on the finite element method. The limbal attachment zone of the TM is firmly fastened to the spiral limbus and it was modeled as the rigid boundary as shown in Fig. 1. Here, the rigid boundary length d = 30 μm, and the lengths a and b are 10 and 50 μm, respectively. We used the width w_T, thickness h_T, and Young's modulus E_T of the *TM* as parameters. Here, the size of the *TM* main body was fixed to $w_T = 3\,h_T$. The width w_B, height h_B, and Young's modulus E_B of the *BM* change according to the location along the cochlea. We used the value of these parameters near the apex; w_B = 0.2 mm, h_B = 6.5 µm and E_B = 40 MPa [6]. The chamber size also changes along the cochlea but we fixed the radius of the chamber to *r* = 0.5 mm for simplicity. The bulk modulus, density, and viscosity of the fluid were 2.2×10^9 Pa, 1.034×10^3 kg/m^3, and 2.8×10^{-3} Pa·s; the Poisson's ratio and density of the *BM* and *TM* were 0.49 and 1.2×10^3 kg/m^3, respectively [15, 16].

3. RESULTS AND DISCUSSION

The previous study showed that there are two types of the *TM* slow waves [7]. Here, we call them *TM* wave 1 and *TM* wave 2. Figs. 2 and 3 illustrate the *TM* and *BM* displacement when *f* = 3 kHz and f = 20 kHz, respectively. The results of (a) *TM* wave 1, (b) *TM* wave 2, and (c) *BM* wave are shown in these figures. The parameters of the *TM* were set as w_T = 120 µm, h_T = 40 µm, and E_T = 50 kPa. Figs. 3 (a) and (b) show that the displacement of the *TM* wave 1 is concentrated on the *TM* limbal attachment zone while the one of the *TM* wave 2 is mainly on the tip of the *TM* main body when *f* = 20 kHz. As shown in Figs. 2 (a) and (b), the displacement of the *TM* waves spreads to the whole part of the *TM* when *f* = 3 kHz. We can see from these figures that the *TM* waves occur the displacement of the *TM* while the *BM* has no displacement. On the other hand, the *BM* wave arises the displacement of both of the *BM* and *TM* as shown in Figs. 2(c) and 3(c).

Figs. 4(a) and (b) illustrate the dispersion characteristics of the phase constant β and attenuation constant α, which are respectively the real and imaginary parts of the angular wavenumber. In these figures, the solid and dashed lines show the results of the *TM* waves while the dash-dotted line shows the one of the *BM* wave. The size and Young's modulus of the *TM* were set as w_T = 120 *µm*, h_T = 40 *µm*, and E_T = 50 kPa. The *TM* waves have larger phase constants than the *BM* wave over the whole frequency range as shown in Fig. 4 (a). It means that the *TM* waves propagate slower than the *BM* wave in the vicinity of the base region. From Fig. 4 (b), we can understand that the attenuation constants of the *TM* waves are much bigger than the *BM* wave. We can estimate that the *TM* waves attenuate in the vicinity of the base, and therefore, the *TM* waves have little influence on the signal that is transmitted by the *BM* wave.

Next, we investigate the structural dependency of the attenuation constants of the *TM* waves. Fig. 5 shows the attenuation constants of the *TM* waves as a function of the thickness h_T, when *f* = (a) 3 kHz and (b) 20 kHz. Here, the Young's modulus of the TM is E_T = 50 kPa, and the size of the *TM* main body was fixed to $w_T = 3\ h_T$. We can see from these figures that as the h_T gets larger, the attenuation constants become smaller regardless of the frequency. The size of the TM becomes larger as the location moves farther from the base along the cochlea. Therefore, the attenuation constants decrease as the location changes from the base to the apex along the cochlea. As shown in Fig. 5 (b), the attenuation constant of the *TM* wave 2 has a considerably large value when *f*= 20 kHz. In this case, the mode field of the *TM* wave 2 is concentrated on the tip of the main body as shown in Fig. 3 (b). As the mode field converges on the tip of the main body, the attenuation constant tends to become larger.

Fig. 6 shows the attenuation constants of the *TM* waves as a function of the Young's modulus E_T, when *f* = (a) 3 kHz and (b) 20 kHz. Here, the size of the TM main body was set as w_T = 120 *µm* and h_T = 40 *µm*. When the frequency is 3 kHz, the amount of change of the attenuation constant with respect to the Young's modulus is small for each mode. On the other hand, when the frequency is 20 kHz, the attenuation constant of the *TM* wave 2 has a large value and the changing rate becomes also larger. This is related to the fact that the mode field of the *TM* wave 2 is concentrated on the tip of the main body.

4. CONCLUSION

We investigated the attenuation characteristics of the *TM* waves. First, we studied the difference of the displacement of the *TM* and *BM* between two types of the *TM* waves and the *BM* wave. We showed that the *TM* waves arise only the *TM* displacement although the *BM* wave induces both of the *TM* and *BM* movement. Next, we showed that the attenuation constants of the *TM* waves are much bigger than the *BM* wave. The results imply that the *BM* wave propagates along the cochlea and culminates at the specific region depending on the acoustic frequency, while the *TM* waves attenuate in the vicinity of the base. The *TM* waves might play an important role in the auditory system by using wave coupling, however, it is presumed that the BM wave plays a main role for transmitting acoustic signals from the base to the apex. Finally, we investigated the dependency of the attenuation constants of the *TM* waves on the size of the *TM* main body and the Young's modulus of the *TM*. We found that as the mode field converges on the tip of the main body, the attenuation constant tends to become larger.

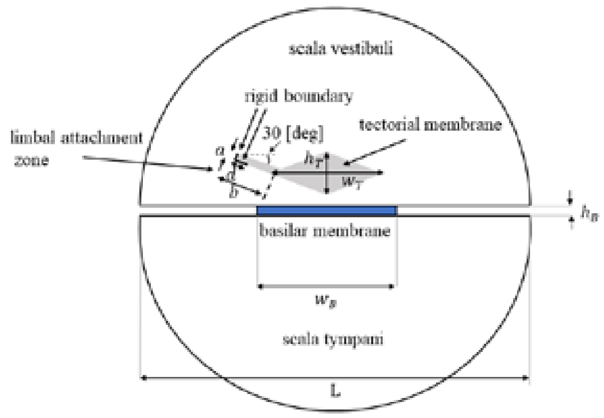
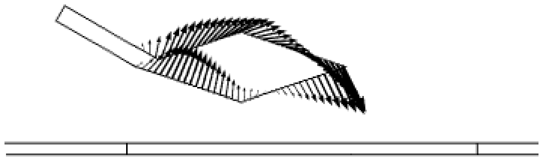
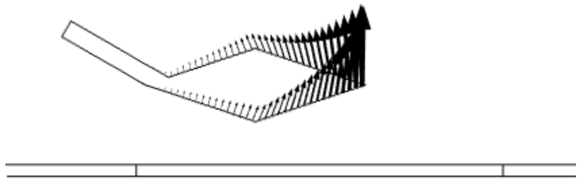


Fig. 1: Analysis model



(a)



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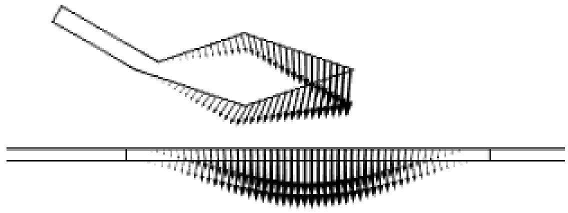
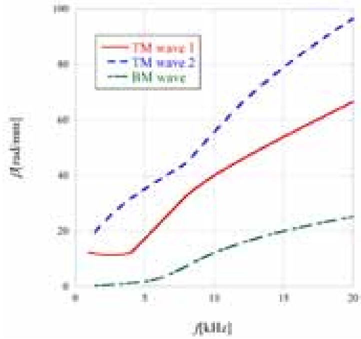
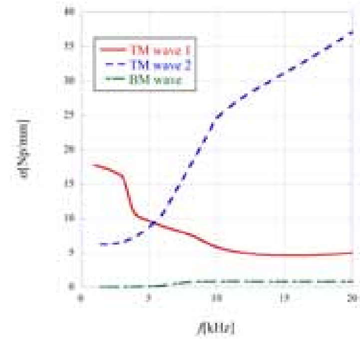


(c)

Fig. 2: TM and BM displacement of (a) TM wave 1, (b) TM wave 2, and (c) BM wave when f =3 kHz

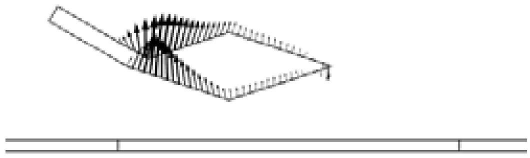


(a)

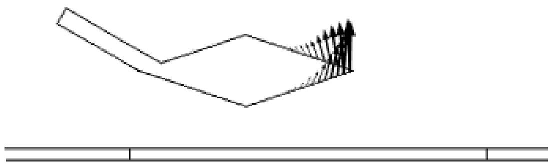


(b)

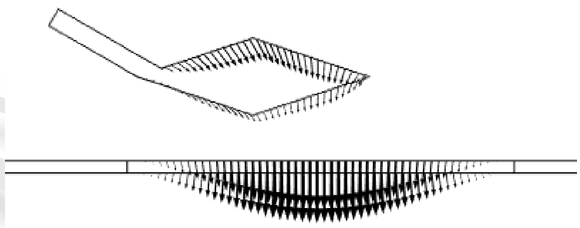
Fig. 4: Dispersion diagram of TM wave 1, TM wave2, and BM wave; (a) phase constants and (b) attenuation constants.



(a)

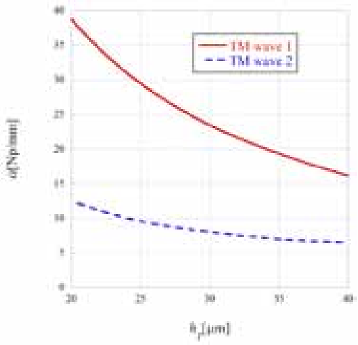


(b)

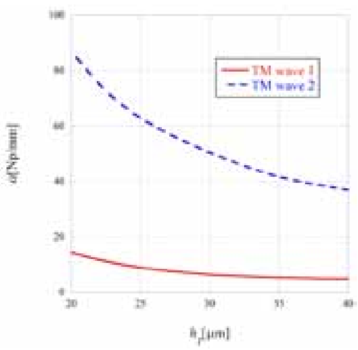


(c)

Fig. 3: TM and BM displacement of (a) TM wave 1, (b) TM wave 2, and (c) BM wave when f = 20 kHz

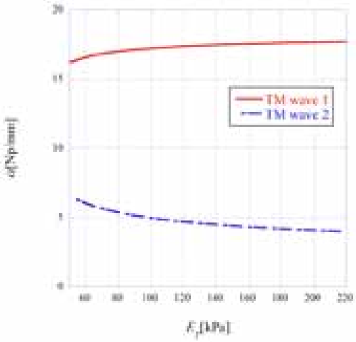


(a)

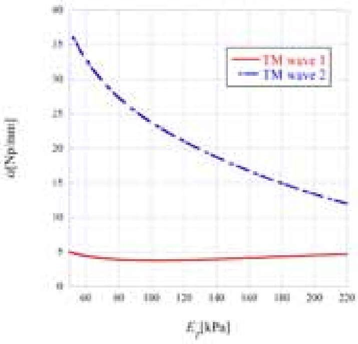


(b)

Fig. 5: Attenuation constants of TM wave 1 and TM wave 2 as a function of h_T when f = (a) 3 kHz and (b) 20 kHz



(a)



(b)

Fig. 6: Attenuation constants of TM wave 1 and TM wave 2 as a function of E_T when f = (a) 3 kHz and (b) 20 kHz

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