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Research paper

Mechanical model of an arched basilar membrane in the gerbil cochlea

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ABSTRACT

The frequency selectivity of a gerbil cochlea, unlike other mammals, does not depend on varying thickness and width of its basilar membrane from the basal to the apical end. We model the gerbil arched basilar membrane focusing on the radial tension, embedded fiber thickness, and the membrane arch, which replace the functionality of the variation in thickness and width. The model is verified with the previous gerbil cochlea model which estimated the equivalent basilar membrane thickness and is shown to be more accurate than the flat sandwiched basilar membrane model. The simple sinusoidal-shaped bending mode assumption in previous models is found to be valid in the present model with $<12\%$ error. Parametric study on the present model shows that fiber thickness contribution to the membrane stiffness is close to the 3*rd* order, higher than the 1*st* order estimation of previous models. We found that the effective Young's modulus of the fiber bundle is at least 6 orders higher than the shear modulus of the soft-cells and the membrane radial bending stiffness is more sensitive to the membrane arch and the shear modulus of the soft-cells near the apical end.

1. Introduction

The mammalian cochlea is a sensitive transducer. It maps the input acoustic energy according to frequency onto the basilar membrane (BM) as vibrations which excite the inner hair cells, sending electrical signal to the brain. The performance of such a system depends on its frequency selectivity where sharper frequency tuning (higher frequency selectivity) signifies that the cochlea is able to discern two signals with closer frequency from one another. The frequency selectivity of a mammalian cochlea predicates on the varying properties of its basilar membrane from the basal to the apical end. These properties are typically the width and thickness in most mammalian cochlea including cat, chinchilla, and guinea pig (Lim and Steele, 2002; Yoon et al., 2011). A recent frequency tuning comparison of mammalian cochlea across species in Ruggero and Temchin's work (Ruggero and Temchin, 2005) indicated that the frequency tuning sharpness of mammalian cochleae are similar among most mammals including the gerbil. Such similar frequency tuning sharpness normally suggests that the gerbil cochlea has a similarly large variation of BM width and thickness. However, in the gerbil cochlea, the width of the BM remains relatively constant from the base to the apex (100% increased (Naidu and Mountain, 2007; Edge et al., 1998)) compared to other mammals such as cat and chinchilla (300% increased (Yoon et al., 2011; Dallos, 1970; Cabezudo, 1978)) and the thickness of gerbil cochlea BM increases slightly (Edge et al., 1998; Naidu and Mountain, 2007) from the basal to the apical end, compared to other mammals such as cat (Cabezudo, 1978), chinchilla (Eldredge et al., 1981), and guinea pig (Wada et al., 1998) which decrease along their cochlea. Without the variation of BM width and thickness to change its radial bending stiffness (y-axis), the BM in gerbil cochlea relies on the fiber bundle thickness as well as its arch toward the scala tympani from base to apex to achieve comparatively sharp frequency selectivity (Chan and Yoon, 2015).

There are various attempts to simplify the unique structural mechanism of the gerbil BM which is flat on the side of the scala

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vestibuli and has an arch toward the scala tympani (Richter et al., 1998; Kapuria et al., 2011) (see Fig. 1). Yoon et al. (2007b) used the flat BM model by inserting estimated effective BM thickness into their mechanical gerbil cochlea model. Although the mechanical gerbil cochlea model formulated with this uniform fiber density model agrees with experimental measurements (Yoon et al., 2007b), the effective thickness in the gerbil model which decreases from basal to apical end of the gerbil cochlea does not represent experimental measurements of the BM thickness of gerbil cochlea (Edge et al., 1998; Naidu and Mountain, 2007). Moreover, the simulated gerbil cochlea using this model (Yoon et al., 2012) deviates from experimental input impedance (Rochefoucauld et al., 2008; Decraemer et al., 2007). Liu and White (2008) as well as Naidu and Mountain (2007) modeled the BM as a composite with fiber bundles across the width of the BM. Liu and White (2008) modeled the fiber bundle as an array of rods at the center of the BM thickness and Naidu and Mountain (2007) modeled the gerbil BM as a sandwich plate with the fiber bundles as two arrays of rods at the top and bottom of the BM. Although these composite models use the experimentally measured parameters, a parametric study comparing these models with experimentally measured BM behavior shows a mismatch in the fluid-mechanical traveling wave number (Chan and Yoon, 2015).

In our previous study (Chan and Yoon, 2015), we have identified the radial bending stiffness, as one of the important factors affecting the fluid-mechanical traveling wave in the gerbil cochlea and shown that previous gerbil BM models (Yoon et al., 2007b; Naidu and Mountain, 2007) are unable to account for significant changes in the radial bending stiffness along the gerbil cochlea. In this work, an arched basilar membrane model is formulated. Although the structural stiffness of composites with complex curve can be simulated with Finite Element Analysis (FEM) (Vafaeesefat and Khanahmadlu, 2011; Jang and Kim, 2012), this approach is less ideal when the deformation of the entire membrane is unknown. The structural model of a complex curve composite is analytically simplified, verified for accuracy against the radial bending stiffness variation of Yoon et al.'s mechanical gerbil cochlea (Yoon et al., 2007a,b) and compared to Naidu and Mountain's sandwich BM model. With the verified model, the stiffness variation with arch shape and fiber bundle thickness are analyzed. The results show that the shearing of the soft-cells and the arch shape of the BM enable significant variation of the radial bending stiffness with lesser dependency on the BM width and thickness than the fiber bundle thickness variation along the cochlea.

2. Model of an arched basilar membrane

The gerbil cochlea BM in this work is modeled as a homogeneous, soft ground substances (soft-cells) sandwiched by fiber bundles lining the top and bottom of the membrane as shown in Fig. 1(a). We used parameters extracted from measurements of gerbil's BM in Edge's work (Edge et al., 1998) as well as the fiber bundle geometries from Naidu et al.'s measurements(Naidu and Mountain, 2007) as listed in Table 1.

Table 1
Properties of Gerbil arched basilar membrane (Naidu and Mountain, 2007; Edge et al., 1998; Schweitzer et al., 1996). The basilar membrane width is the measurement of the pectinate zone.

Distance from base,x(mm)	3.61	6.86	11.24
BM Area,A(μm^2)	3998	7005	8225
BM height,h(μm)	35	49.7	55.3
BM Width,b(μm)	168	192	207.3
Fiber thickness,t(μm)	1.02	0.57	0.28
Fiber width,d_{width}(μm)	1.13	0.8	0.35
Fiber spacing,$d_{spacing}$(μm)	1.6	1.62	1.67

2.1. Basilar membrane fiber bundle

The arched fiber bundle is approximated to a rectangular cross-sectional beam of thickness t, width d_{width}, with an arch profile w_0 (see Fig. 1(b)) and a radius of curvature, R. With the following assumptions;

1. The cross-sectional plane cut through the center of curvature and remains in a plane after bending.
2. The radius of curvature is much larger than the thickness, $R \gg t$.
3. The deflection of the arched fiber, w_p, is small.

The strain along the with of the BM, ε_{yy}, is,

$$\varepsilon_{yy} = \frac{\delta\alpha}{\delta\theta}\left(\frac{R_n}{r} - 1\right) \tag{1}$$

$$\frac{\delta\alpha}{\delta\theta} = -\frac{\delta^2 w_a}{\delta y^2}\frac{R}{\gamma} \tag{2}$$

$$R = \frac{\gamma^{3/2}}{\frac{\delta^2 w_0}{\delta y^2}} \tag{3}$$

$$\gamma = \sqrt{1 + \left(\frac{\delta w_0}{\delta y}\right)^2} \tag{4}$$

where R_n is the radius of the neutral axis, R is the radius of

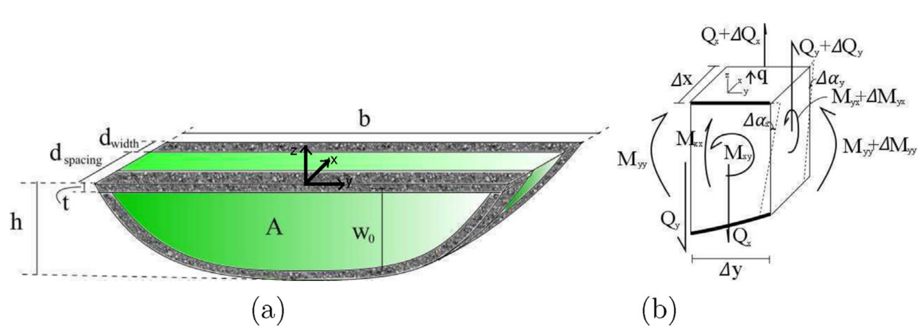

Fig. 1. (a)Illustration of the pectinate zone of present arched basilar membrane model with denotation on parameters of the basilar membrane and (b) a section, $\Delta x\Delta y$, of the arched plate showing forces on the section. M and Q are the external moments and shearing force in the respective axes. $\delta\alpha$ is the change in angle of the cross-section plane in the respective axes and q is the z-direction pressure on the BM section.