# A Three-Dimensional Model Of Human Stereocilia Nano Deflections Under Basilar Membrane Vibration

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## 1. Introduction

It is intriguing how the ear works to amplify the sound signal. The deflection motion of stereocilia is the central mechanics to transduce the power of acoustic vibrations into the neural impulses. During acoustic stimulation, the basilar membrane (BM), where the organ of Corti rests, vibrates transversely and pushes the outer hair cells (OHCs) towards the tectorial membrane (TM) [1]. Numerous cochlear models have been used to explain the biomechanical behavior of the BM and TM motion [2-4]. The stereocilia bundles at the top of the OHCs are then deflected by the shearing motions between the TM and the reticular laminar (RL). A prevailing theory suggests that the nano-scale deflection towards the tallest stereocilia opens the transduction channels on top of the stereocilia, while the deflection in the opposite direction closes the channels [5]. When the channel opens, the positive ions in the environment enter the OHC and trigger a cascade of events, resulting in the active amplification of the hearing system [6-7].

It is believed that there is a strong correlation between the structural variation of the stereocilia and its deflection motion. In the present work, we built a 3D human model at the region of 500 Hz to study the initial insertion angle of the OHC stereocilia into TM and its effect on stereocilia's deflection motion for the first time. Taking the maximum threshold velocity of the BM as the input velocity of the RL [8], the results suggest that there is an optimum value for this angle at which the stereocilium deflects the most. In this case, the angle is 5 degrees. It indicates that, to enhance the amplification gain and frequency selectivity, the insertion angles of stereocilia at different place *in vivo* shall be equal to the optimum values at their respective place. If not all the angles of the tallest stereocilia in a bundle take the value of the optimum angle, they shall be within certain range to ensure the gain of the vibration (maximum displacement of the stereocilium tip in the radial direction versus the maximum displacement of the RL in the transverse direction) to be more than 1. For the 500 Hz region in the human cochlea, the range is suggested to be less than 30 degrees.

## 2. Method

To model the interactions between the TM and a stereocilium, the TM was simulated as a 3D plate with dimensions of 4 × 2 × 4 μm in the x-y-z directions (radial-transverse-longitudinal). The stereocilium was modeled as a constant diameter rod capped with a sphere (Figure 1). The length and diameter of the stereocilium was 5 μm [9] and 300 nm [10-11] respectively. Initially, it was inserted 100 nm into the TM and was oriented at 0 degrees with respect to the lower surface of the TM [10-11]. The problem was solved in finite element method (FEM) by using COMSOL software. An increment of 5 degrees was added to the insertion angle for each evaluation until it reached 40 degrees.

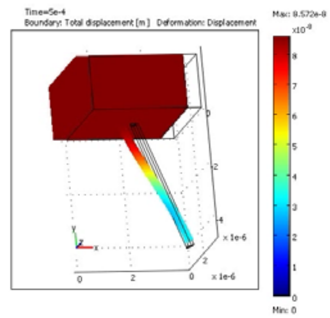


Figure 1 Evaluating the correlation of stereocilium's initial insertion angle and its deflection motion by FEM. A 5-μm-long stereocilium is embedded 100 nm initially inside of the TM. A force in the form of a sine wave is applied for one period at the bottom of the stereocilium towards the y direction. The stereocilium and the TM are displaced radially from their starting position (white wireframe) to a maximum displacement at time of a quarter of a period. Colors represent the total displacement distribution in the model.

The force from the BM was considered as the only input of the model [12]. It was simulated as a prescribed displacement at the stereocilium's base along the transverse direction (y axis) in the form of a sine wave, with maximum velocity 100μm/s and frequency 500 Hz, lasting only one period. The other two directions of the rod base and the transverse displacements of the TM were constrained [13].

The material properties of the stereocilium was taken the same as that of actin, $3\times10^9$ N/m$^2$ [14]. The properties of the TM were taken from table 1 [15]. The stereocilium's and the TM's Poisson's ratio and density were taken as 0.4 and 1200 kg/m$^3$ respectively [16].

Table 1 Orthotropic mechanical properties of TM

| Model | X (radial) | Y (transverse) | Z (longitudinal) |
|---|---|---|---|
| E (kPa) | 11 | 28 | 16 |

## 3. Results and discussion

Figure 2 is the plotted graph of the maximum displacements of the stereocilium tip in the three directions versus the initial insertion angles. Since the radial direction (x direction) is the tilted direction of the stereocilium and also the direction of smaller young's modulus for the TM, the displacement in this direction is much more than that in the other two directions. During the bending process, stereocilia transform their vibration energy in the transverse direction to that of the TM in the radial direction.

The results suggest that 5 degrees is the optimum angle for the human stereocilium to insert into the TM initially at 500 Hz region. With different young's modulus of TM, initial insertion length and morphology of the cilia, this optimum value shall be different along the cochlea. More modeling needs to be conducted at places other than 500 Hz region to generalize the findings. However, the lack of human cochlea parameters puts a restriction in conducting such modeling at present.

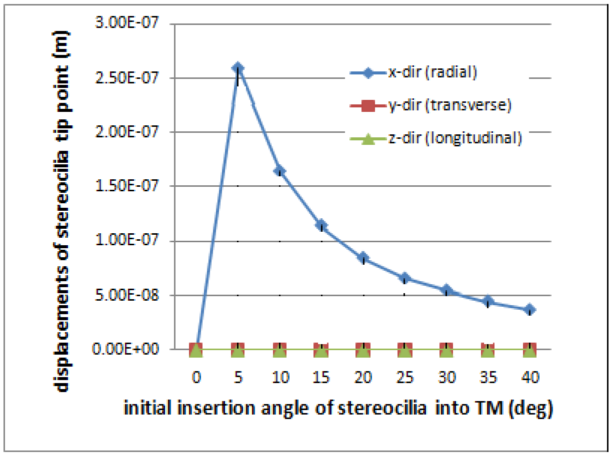


Figure 2 Displacements of outer hair cell stereocilia tip point versus initial insertion angle of stereocilia into TM curves acquired at 500 Hz region of human cochlea model. Blue, red, and green lines indicate the displacement in the radial, transverse and longitudinal directions respectively.

By comparing the input and output, it is found that the maximum displacement of the input, 3.1 x $10^{-8}$, corresponds to an angle between 30 to 35 degrees in the output graph. That is, for angles less than 30 degrees, the gain (output/input) is more than 1. It suggests that in vivo, for human cochlea at 500 Hz region, the initial insertion angles of stereocilia into TM are less than about 30 degrees, if not all at 5 degrees, as this could enhance the amplification gain and frequency selectivity.

Comparing with the measurements of guinea pig stereocilia [17], the value of stereocilium tip displacements in the radial direction are in the same magnitude of $10^{-7}$. The stereocilium base displacements in the transverse direction are also in the same magnitude of $10^{-8}$. These indicate the consistency of the model with the reality. However, there might be discrepancies due to the estimated mechanical properties of the model.

## 4. Conclusion

Based on reasonable assumptions and parameters, a 3D model is successively built to show the interactions between stereocilium and TM. It is in reasonable magnitudes compared with experimental data.

With an initial inclined insertion angle, cilia tip has negligible displacements in longitudinal and transverse directions compared with that in the radial direction. When the stereocilium is pushed towards the TM, it transforms its vibration energy in the transverse direction to that of the TM in the radial direction.

The result shows that, for human model at 500 Hz region with its threshold maximum vibration velocity of 100 μm/ s, the optimum initial insertion angle of stereocilium into TM is 5 degrees. At this angle, the stereocilium deflects the most. Thus, to enhance the amplification gain and frequency selectivity, the insertion angles of stereocilia in vivo shall be equal to this optimum value. If not all the angles of the tallest stereocilia in a bundle take the value of the optimum angle, they shall be within certain range to ensure the gain of vibration to be more than 1. For the 500 Hz region in the human cochlea, the range is suggested to be less than 30 degrees.

In future, the results of this work could be generalized by modeling at different places along the cochlea. The model could be enhanced by incorporating the cross-links of stereocilia and other varying factors, such as the mechanical properties of TM, the morphology and initial insertion length of the stereocilium.

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