FOUR- CHAMBER COCHLEA BOX MODEL: ESTABLISHING ACOUSTIC COMFORT, ILLUSTRATING INJURY AND TOWARDS THERAPY

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Abstract: The unrolled cochlea is modeled using the finite-element software ANSYS, with four inner chambers representing the Scala Vestibuli contiguous with the Scala Tympani thru a rounded helicotrema, the Scala Media, the inner and the outer hair cells. The tectorial membrane is represented as a plate in contact with the hair cells. An improvement to previously presented results is the inclusion of a tapered helicotrema. Various geometries are compared, i.e. with straight sides and with tapered sides, and see the differences in the frequency response of the models. Applying real values for material properties and the human hearing range and using characteristic frequency at certain nodes inside the Scala Media, the tapered model is calibrated to establish the reference comfort. Hearing injury is regarded by subjecting nodes to increased sound pressure levels until the frequency response disappears. This is done at the same time monitoring the change in electrical potential in the inner and outer hair cell regions. The potential change between the normal and the injured conditions is inputted to the Gibbs energy equation for the ATP-ADPase glycolysis to identify a possible route to remedy.

Key words: Cochlea, ANSYS, Hearing Injury, Therapy, Thermodynamics

1 INTRODUCTION

The human cochlea is located in our inner ear region and is responsible for transforming the sounds we hear into electrical signals passing them to the brain for processing and interpretation. The cochlea in vivo is a tapering, spirally coiling, fluid filled, complex organ, however unrolled box models (See Fig 1.) are frequently used in theoretical studies (Neely and Kim, 1986; Steele and Kim, 1999; Nobili and Vetesnik, 2005) or in basic configurations in the development of prototype micromechanical hearing devices.

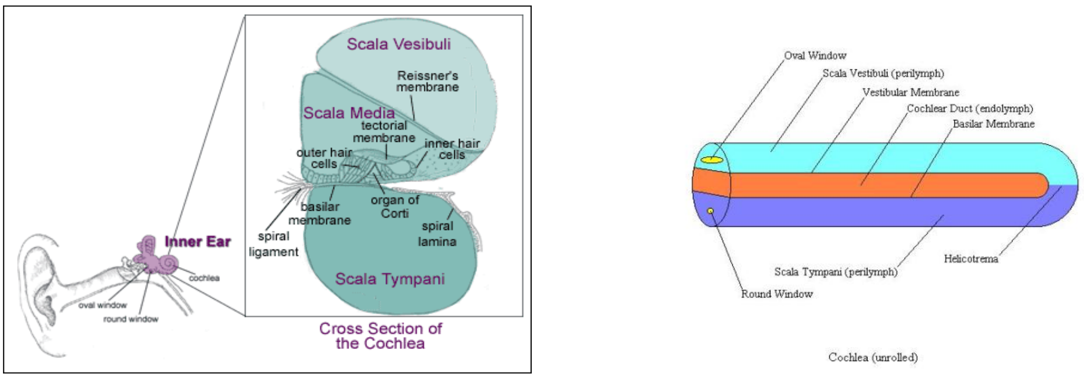

Figure 1 The Cochlea. Upper left is the cochlea's location, natural shape, cross section and main parts; upper right is an example of an unrolled model cochlea showing the compartments. Left image adopted from www.osha.gov; right image from www.etsu.edu .

Sound enters through the oval window, travels along the SM around the helicotrema and excites the SM membranes. In turn inside the SM, the motion of the TM causes the inner and outer hair cells to react by sending electrical signals to the nervous system. Hearing loss can actually be seen as damage to these hair cells. It has been observed that during noise-induced hearing loss, there is a surge of reactive chemical species, e.g. oxygen (Talaska and Schnaht, 2007).

The objective of this study is to provide preliminary insight into cochlear mechanics towards alleviating damage to hearing. We employ thermodynamics to find a rationale in wrestling with the chemical imbalance. The advantage of using thermodynamics is its ability to describe bulk properties (Prausnitz, 2003). The alleviation of the damage can either be by diet therapy metabolism or drug delivery.

2 METHOD

The actual cochlea has a diameter of around 9 mm and a length of about 350 mm, though model dimensions range variably (Gan, et al, 2006; Grivelberg and Bunn, 2002). Below in Fig. 2 is our model with dimensions 4x4x35 mm delineating the SV/ST chambers as joined by the helicotrema, the SM, the IHC and the OHC regions.

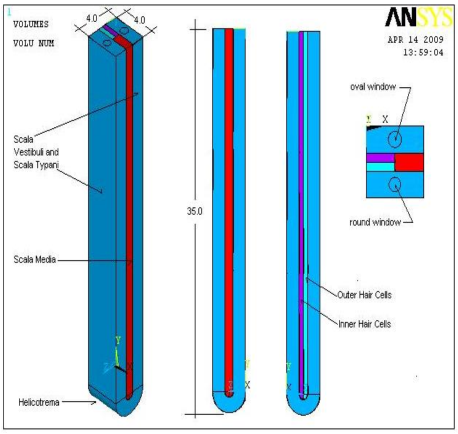

Figure 2 Cochlea Model

Using ANSYS, we assign FLUID30 element to account for the fluid-structure interaction as sound along the SV/ST provides pressures and displacements along the SM. The TM is modeled using SURF154 as a plate attached to the SC having contact with both the OHC and the IHC. The OHC/IHC regions are assigned SOLID98 which has mechanical-electrical coupling properties. We establish the reference comfort level and then illustrate hearing injury while at the same time monitor the change in electrical potential. The potential change is inputted to the Gibbs energy equation for the ATP-ADPase glycolysis (Kondepundi, 2008). Although the ear fluids involve the K^+,Na^+-ATPase process (O'Beirne and Patuzzi, 2007) we observe that most of the studies are qualitative. However, the ADP-ATPase glycolysis underlies all biological processes (Beard and Qian, 2008).

Material properties for the cochlear structures are 1000 kg/m^3 for the SV/ ST fluids while 1100 kg/m^3 for SM/TM and 1200 kg/m^3 for the OHC/IHC, the viscosity of the SV/ST fluid is 0.7 x 10^{-3} Pa-s. We assumed the Young's modulus is 45 MPa for the SM/TM and 7 MPa for the OHC/IHC, the Poisson ratio is 0.3 for the SM/TC and 0.1 for the OHC/IHC. A shear modulus of 0.003 MPa is assigned to the OHC/IHC.

During simulation material properties were transformed to uMKSV system. We only use linear damping to investigate the displacement. The frequency range tested is from 0 to12000 Hz.

3 RESULTS

In order to calibrate the model, responses at the interior of the SM at node 1923 located at X= 3.32, Y=1.28, Z=1.90 mm are shown in Fig.3.

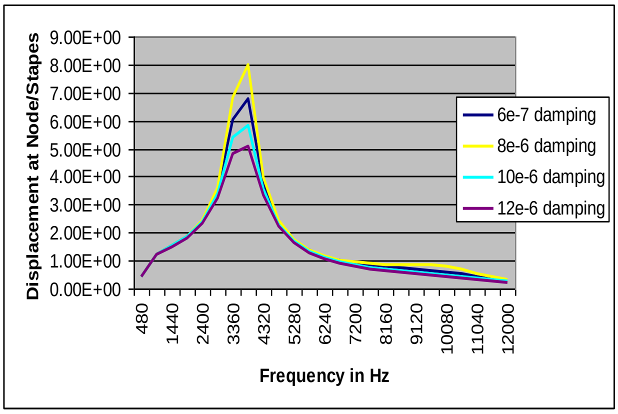

Figure 3 The displacement at node 1923 with respect to oval window at 50.17 dB in the range 0-12000 Hz.

The frequency response of the node is with respect to the displacement of the oval window which can be directly read. The damping variation centers around a characteristic frequency of 4320 Hz. To calculate the equivalent dB we apply from ISO 140-6(E) the equation

$$L = 10 \log n \frac{p_1^2 + p_2^2 + \ldots + p_n^2}{n\ p_0^2} \qquad (1)$$

where p_i are the sound pressure levels at n different position and p_0 is equal to 20 uPa. In this case we take n =8049 which is the total number of nodes of the model. The value obtained is 50.17 dB which is also within the comfortable range of hearing. Next we subject the model to its maximum allowable damping by ANSYS which corresponds to 80.42 dB. However at that hazardous sound level, displacements at a majority of the nodes upon damping variation are already identical flat lines.

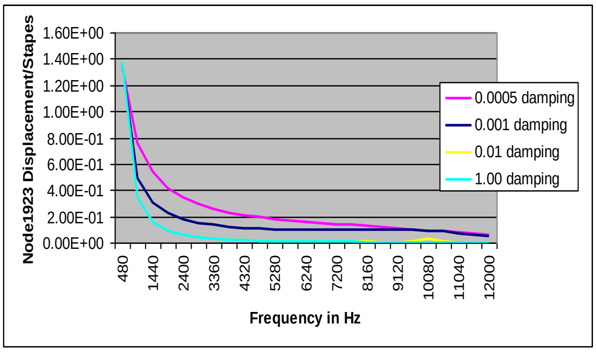

Figure 4 The displacement at node 1923 with respect to the oval window at 80.42 dB in the range 0-12000 Hz.

In Figure 4 we plot the initial flattening of the response, as a sign of injury to hearing at node 1923. Corresponding to the comfort and injury conditions we look at the OHC/IHC regions and investigate the change in electric potential. The OHC and the IHC were respectively assigned initial potentials of -70 mV and -45 mV (Mistrik etal, 2009).

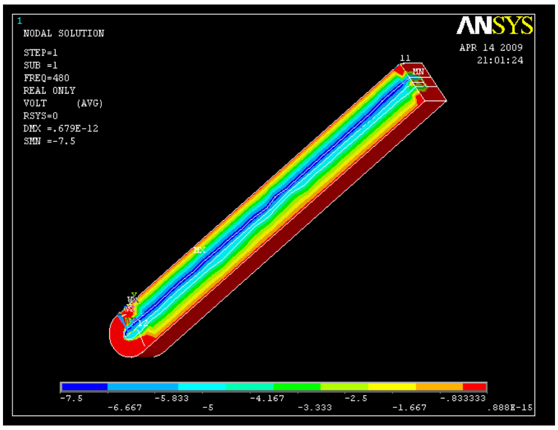

Figure 5 Snapshot of the time-development animation of the potential at node 1923 at 50.17 dB in the range 0-12000 Hz.

A snapshot of the ANSYS animation showing the potential in the OHC/IHC is shown in Fig. 5. We read from the simulation that in comparing with the potentials during the assumed injury there is a discrepancy of -100 mV or of two orders of magnitude. We use this value as the heuristic discrepancy in the Gibbs energy equation describing ATP synthesis during glycolysis. Such a process is present during transport of biomolecules and forms part of the so called K^+-Na^+ pump (Kondepundi, 2008). In addition, electric potential can be related to the Gibbs energy through the equation $\Delta G = \Delta\Psi - T\Delta E - V\Delta Q$, where G is the Gibbs energy, Ψ is the Helmholtz energy, T is the temperature, E is the internal energy, V is the volume and Q is the charge in volts (Deo and Grosh, 2004). We treat all variables constant except Q. In other words what we are putting forward is that an introduction of a chemical reaction which will induce an increase of two orders of electric potential can mediate the chemical imbalance in the cochlea and alleviate hearing injury.

4 DISCUSSION

The subject as presented here can be considered only as an academic exercise ─ as an initial foray through ANSYS and relevant literature into the cochlear mechanics. It is worth mentioning however that the use of thermodynamics in cochlear studies has not been fully exploited especially in the OHC/IHC regions. The plots in Fig 2 are similar to the BM displacement vs. frequency plots (Steele and Kim, 1999; Gan etal, 2005) showing the sharp increase then the sudden drop. Our results however show an extended tail which can be attributed to the fact that the whole regime is linear. Deo and Grosh (2004) used Gibbs energy more to investigate OHC mechanical properties. To the best of the authors' knowledge, modeling of cochlea injury in bulk is lacking in literature. Though the study aims to cover a broad physiological phenomenon, the current state sees much refinement, i.e. geometry and nonlinear effects.

5 CONCLUSION

We consider the entire cochlea and to model using ANSYS basic cochlea phenomena and injury and using thermodynamics hypothesize a basis for therapy.

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