A Modified 3-D Model for the Basilar Membrane under the Influence of the Inner-Ear Fluid Properties

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Abstract

This paper develops an interaction 3D model for the basilar membrane inner ear fluid-structure explaining the uncoiled cochlea with a determination in the domain of the time. The model predicts and forecasts the amplitude vibrations of the Basilar Membrane (BM) together with the pressure wave's magnitude in the two conditions. The 3-dimensional model is assessed in terms of responses that are dynamic to the cochlea. The study uses the short-term time frontier sounds, as well as unsteady phenomena to show such kinds of responses. Addition aim is to compare the outcomes with a one-dimensional mass- spring –damper approach. Several experiments have been carried out regarding the characteristics of frequency position, cochlea differential pressures, oval window (OW), the round window (RD), amplitude of deflection and the velocity of the stapes footplate (SF). These experiments are extremely hard to conduct and however, they provide much significant information. To solve this complexity, some of the helpful tools are used including numerical tools that can complete and extend the physiology understanding of the cochlea. The outcome of the time -domain, fluid-structure interaction (SFI) that is focusing on the (BM) vibrations is presented. The micromechanics of the cochlea calculations, as well as comparisons with the simple mechanical ID models, are considered.

Key words: Basilar membrane, cochlea, frequencies, Fluid, cochlear mechanics.

Introduction:

Most of the developed cochlea models depend on the method of analogy modeling. These models are used for purposes of developing and constructing pathological and normality of the middle and the inner ear behavior. This category of the modeling generates efficient outcomes and results that provide a correlation with experimental data. However, their parameters are indirectly connected to the physiological and anatomical aspects; this represents one limiting factor for the usage of the models in the assessments of hearing development approaches. [3]

The other category of models is used to resolve the flow of cochlear fluids where the equations combined with mechanical equations of the basilar membrane. This is primary for both the 2-dimensional and 3-dimensional equations. The second category models also have the capacity of predicting the cochlea macro-mechanics, although these require very complex solutions.

Mechanical Properties of the Basilar Membrane

The basilar membrane as a part of the mammalian cochlea has a very vital role it plays in the mechanical processes that occur before encoding sound information into its auditory nerve. The basilar membrane variations are likely to be critical especially with the various phenomena. These include sound frequencies separation along the cochlear length. Mathematical modeling and simulations are now explaining many mechanical aspects of the basilar membrane such as the coupling lying along with its length and the elastic properties variations across the basilar membrane width. The stiffness and target gradient along the basilar membrane length and the role of the stiffness gradient are also other aspects to consider. This is to account for the cochlea map frequency-place.

[12,8]

Irrespective of the basic concerns of the cadaver preparations of freshness, the magnitude of the base-to-apex gradient of stiffness is significantly close to the values of the basilar membrane. Investigations have provided information concerning the point stiffness as a function of tissue for every deflection site. Olson and martin (1991) observed that the initial stiffness plateau has its length depends on the noise level. Secondly, a quadratic increase in stiffness tends to be over the second plateau and this extends the stiffness point measurements. This is for the positions that span with the whole width of the basilar membrane. They also determined that the next spiral lamina plus the spiral ligament, stiffness is relatively high as deflection increases. On the other, with the accurate zone, the basilar membrane tends to be a little complaint.

It also shows a monotonic increase in the stiffness as tissue deflection increases. At the lower end of the outer foot of the pillar cell, the basilar membrane appears to show a plateau that is relatively stiff. This is also followed by a quadratic increase in the stiffness as deflection also increases. The plateau stiffness magnitude that is determined at the pectinate area appears to be within the range of that measured at the arcuate zone and the one below the outmost pillar foot. [2],[8]

Concerning the deflections that are beyond the plateau, stiffness increases in a quadratic manner. When the stiffness measurements are made in a vitro gerbil cochlear turn preparation, the deflection of stiffness appears to be curved. This happens normally at a specified position, a length that lies along the cochlea. The basilar membrane stiffness and its longitudinal gradient that is measured at a length of 1-4, 8, and 2 mm would result in reductions of about 56 starting at the base to the apex. At locations that are radical and below the outer pillar foot, those at the outer hair cells (OHCs) the factor of 56 still applies. On the other hand, the stiffness below the arcuate area decreases by around 20 from the base to the apex. Approximate measurements of the basilar membrane show a parallel beam structure. The plateau stiffness, on the other hand, presents the beam stiffness and hence the stiffness of the basilar membrane that is physiologically relevant to the basilar membrane. The ground substance and cells of the basilar membrane could result in approximate shear and low strengths; this is because of the incompressibility of the fluid layers. From the point force perspective, all these layers can appear to be floppy and relative especially for the fibers that are embedded until they become fully compressed. [8,12]

The two layers at all tissue deflections would be uncompressible regarding the distributed pressure. Considering the physiological situations, the fibers embedded would effectively dominate the compliance of the basilar membrane. In such a scenario, the relevant physiological data can be obtained from the structural properties measured from the fibers.

The fibers are designed to utilize the spatial frequencies of the cochlea. This is due to the almost uniform innervations that lie along the basilar membrane section. The hair cells located between the basilar membrane and the tectorial membrane form what is known as the Corti. Due to impacts of the mechanical properties, the Corti organs together with the complex sounds are decomposed to form spectral series of signals that are then transmitted along with the partition. At the low levels of sound pressures, the basilar membrane tends to have vigorous responses especially with low frequencies at the apex and with high base frequencies. To respond to complex signals with a wide range of frequencies, the information cloud avails a better form of resolution of the spectrum of the stimulus.

One of the most critical aspects of the basilar membrane is that it does not appear uniformly, it has mechanical properties that vary continuously especially along the length in two major ways.

In the first place, it has a wide membrane at the apex as compared to the base factor of about 5. Secondly, the stiffness of the membrane tends to decrease especially from the apex towards the base by an estimate of about 100 times as shown in fig (1) 12, 2]

Fig. 1: Representation of the variation in width and along the length of the basilar membrane.

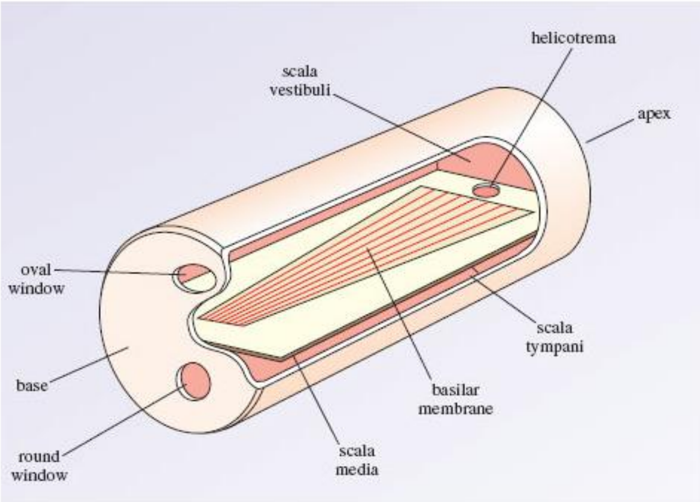
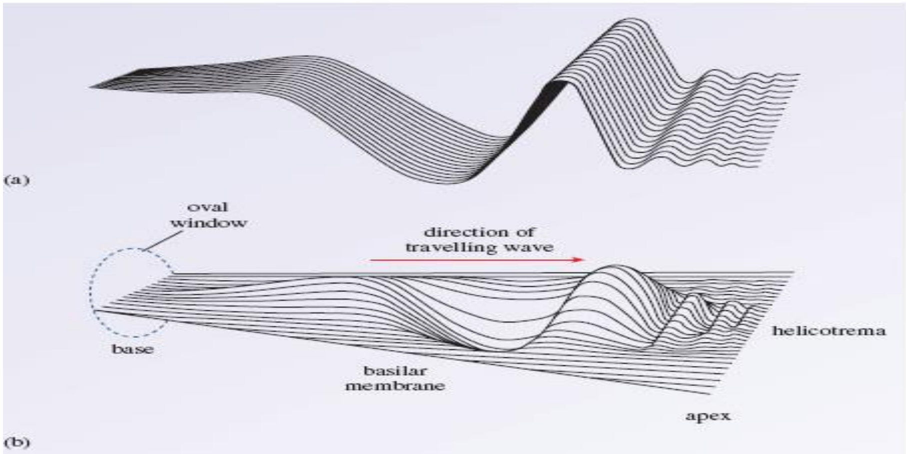


Fig (1) shows that the membrane has a narrow and stiff base as compared to the apex; this implies that the pure tone leads to complex movements of the membrane. Had it been uniform, the fluctuating pressure differences between the Scala Vestibule and the Scala Tympani would cause the entire membrane to move. The down and upwards movements would be equal and having the same excursions at all locations. Since the oscillations between the width and stiffness are not in phase, every membrane segment experiences a single vibration cycle. However, at any single part of the membrane, there are up and downwards movements. This is what is called the traveling wave. It is illustrated in fig (2) [10,12]

Fig.2: Traveling Pattern of Traveling Wave



A traveling wave can then be defined as a unique traveling form of a wave whose point of optimal displacement clears out a particular location sets. This shows that the traveling wave traces out in such locations is what is called the traveling wave envelope. The location along the basilar membrane reaches the optimum is not the same for every single frequency, in summary, therefore, this means that every location along the basilar membrane that goes in motion tends to have a similar vibration frequency. This frequency is the same as the sound of the impinging sound on the ear, although sounds with different frequencies cause varying peaks in the waves. This change in the wave peaks also varies with the varying positions and locations along the basilar membrane.[10]

Development of the 3D model

Most complete models that belong to fluid coupling have to include the 3D fluid effects. This takes place near the basilar membrane and in the wavenumber domain, where the 3D fluid coupling is presented. Recently, there have been formulations in the acoustic and spatial domains and this fluid coupling is considered components sum. This is due to effects such as the 1D, together with the near-field effects. In general, a cochlea box belongs to the 3D of the cochlea because the fluid within can move in any direction. The assumption in this work is that the box is symmetric and the fluid chambers below and above the basilar membrane have an equal area. This also means that the distribution of pressures (p) in these chambers is also the same. The fluid is assumed incompressible and therefore, conserving the fluid mass would lead to equation (1). This leads to the assumption that the basilar membrane distributes its velocity across the width and the longitudinal direction.

$$\frac{\partial^2 p(x,y,z)}{\partial x^2} + \frac{\partial^2 p(x,y,z)}{\partial y^2} + \frac{\partial^2 p(x,y,z)}{\partial z^2} = 0 \quad , \qquad (1)$$

This is assumed to happen in a sinusoidal manner with the wavenumber being k such that:

$$v_{BM}(x,y) = v(x)\varphi(y) = V(k)\varphi(y)e^{-ikx} \quad , \qquad (2)$$

In equation (2), $v_{BM}(x,y)$ represents the velocity distribution of the basilar membrane. This also lies along the cochlea, the variable $\varphi(y)$ represents the velocity distribution of the basilar membrane in a transverse direction, and the parameter k represents the variation of the sinusoidal wavenumber. This distribution of such a transverse movement is however very complex. It is also a level dependent within the real cochlea.

Even though several studies argue that the basilar membrane mode shape is the best type of experiment, fluid coupling does not depend entirely on conditions of the tested boundary of the basilar membrane.[13] Therefore, the distribution of the basilar membrane velocity takes the following mode within the cochlea box model:

$$\int_0^W \varphi^2 (y) dy = W \quad , \quad (3)$$

Where BM here represents the separation between two chambers of fluid, W represents the width of chamber fluid

In equation (3), v(x) would be obtained from I_{BM}(x, y) as:

$$v(x) = \frac{1}{w} \int_0^W v_{BM}(x, y) \varphi(y) dy \quad , \quad (4)$$

On the other hand, the pressure field that acts on (BM) is represented through a mode of summation as:

$$P(x, y, z) = \sum_{n=0}^{\infty} B_n \emptyset_n (y, z) e^{-ikx} \quad , \quad (5)$$

Where B_n represents the modal amplitude with the wavelength rotating around the conditional boundary of BM.

In this type of equations, the variables $\emptyset_n(y, z)$ should meet the boundary conditions of the field. This can then give rise to a pressure parameterization that is suitable for mode shape. Then, the following equation can be developed and applied.

$$\emptyset_n(y, z) = \cos\left(\frac{n\pi y}{W}\right) \cosh[m_n(z - H)] \quad , \quad (6)$$

H portrays the height of the chamber fluid, m and n represent coupling values on velocity in the modal If each of the variables in the model is to satisfy the conditions of mass conservation, the real parameter is given as m_n has to meet the condition below:

$$m^2{}_n = k^2 + \frac{n^2 \pi^2}{W^2} \quad , \quad (7)$$

Coefficients B and n can then be calculated with the boundary condition under the Basilar membrane such that:

$$\sum_{n=0}^{\infty} B_n \frac{\partial \emptyset_n(y,z)}{\partial z} = -2i\omega\rho V(k)\varphi(y), at z = 0 \quad , \quad (8)$$

And this would lead to the equation (9) if equation (6) is substituted into equation (8) as :

$$\sum_{n=0}^{\infty} B_n m_n \sinh(m_n, H)\, cosh\left(\frac{n\pi y}{W}\right) = 2i\omega\rho\varphi(y)V(k) \quad , \quad (9)$$

By cross-multiplying, each side of the above equation (9) with $\cos(\frac{n\pi y}{W})$ and then integrating it from 0 to W over, the resulted model is:

$$B_n = \frac{2i\omega\rho A_n}{m_n \sinh(m_n H)} V(k) \quad , \qquad (10)$$

Here, the coefficient of coupling for n variable would be equal to zero with the description as follows:

$$A_0 = \frac{1}{W}\int_0^W \varphi(y)dy \quad , \qquad (11)$$

Equation (12) represents the pressure modal through an analogy with the velocity as:

$$p(x) = P(k)e^{-ikx} \quad , \qquad (12)$$

Where $P(k) = 2i\omega\rho\left[\frac{A_0}{K}\coth(kH) + \sum_{n=1}^{\infty}\frac{A_0^2}{2m_2}\coth(m_2 H)\right] \quad , \qquad (13)$

The pressure difference in the wavenumber domain occurs as :

$$P(k) = 2i\omega\rho\varrho(k)V(k) \quad , \qquad (14)$$

Where Q(k) has the length dimensions that are termed as equivalent height. In the 3D scenario, the final form of Q_{3D} (k) is obtained and is fully represented as :

$$\varrho_{3D}(k) = \frac{A_0^2}{K}\coth(kH) + \sum_{n=1}^{\infty}\frac{A_n^2}{2m_2}\coth(m_n H) \quad , \qquad (15)$$

Depending on the fluid coupling of the 3D expression in the cochlea, the 1 and 2D formulations can be generated.

Analysis of the Model

With the nonlinear cochlea 3Dmodel, the differences of the sinusoidal pressure moving across the cochlear plane (CP) tend to generate sinusoidal basilar membrane velocities. The existing relationship between these two is simply reflected through an impedance function. The waveform that represents the velocity of the basilar membrane becomes disrupted. Whereas linear systems do not appear in the stimulus spectrum, any (nonlinear system produces harmonic alterations. This normally happens in response to tonal stimuli. The other complex stimuli result in more complex distortions of the spectra product. Nonlinearity can then be generated through a process that defines other nonlinear components and elements. These types of elements, however, include damping, (OHC) force that is characterized as being nonlinear as well as nonlinear in their geometry.[5]

The existing relationship between the pressure differences (p) and the basilar membrane (ω) in the individual locations x on the cochlea length are represented by approximation of the longwave, as in equation (16) :

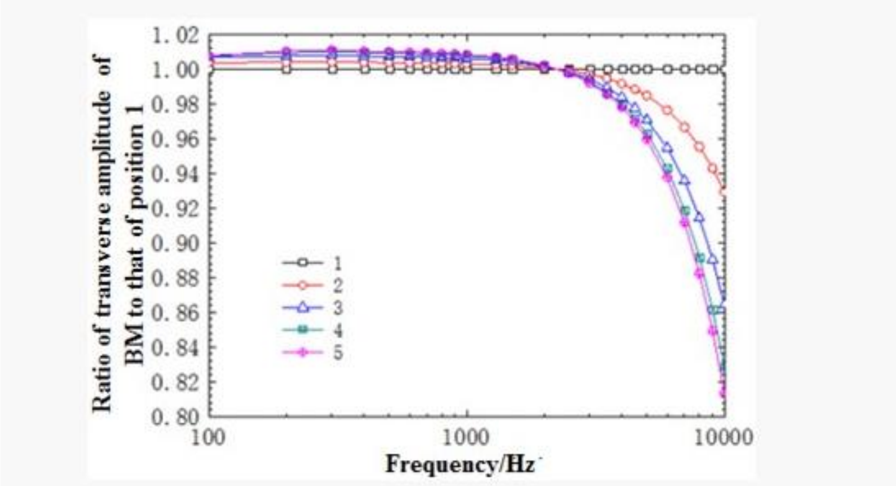
$$\frac{\partial^2 p(x)}{\partial x^2} = -\frac{2\rho}{h}\omega\ddot{(x)} \quad , \qquad (16)$$

In equation (17), the dynamics of the basilar membrane is interconnected with the pressure differences as :

$$p(x) = m(x)\omega\ddot{(x)} + r(x,\dot{\omega})\dot{\omega} + s(x)\omega \quad , \qquad (17)$$

In equation (17) , the variables $r, m,$ (x,ω) together with s(x) represent the mass, damping and system stiffness. It should be noted that the mass is always considered constant. In the equation above, the damping variable is the velocity function of effective frequency and it is dependent on the level of input. The limiting variable or term in the equation is assumed the frequency since the amplitude is next to zero. Basing on such a model, distortion outcomes or products and other basilar membrane phenomena in motion can be determined. The model also has effective linear behavior especially at low levels of input. At the high levels, there is a tendency of the model behaving nonlinearly and this happens in a transmission-line model of the cochlea. The basilar membrane response and products of distortion are used to define the resistance of nonlinearity. According to the oscillator theory, the oscillator displacement is used to describe the mass-spring damped system. The damping term, however, is not linear and it has a negative result especially for the small amplitudes The large amplitudes together with the large velocities tend to have proportional damping terms. Thus, it generates a power of 1/3/dB/dB in particularly with the input-output level of the curve. The sounds with high frequencies can only cause the basilar membrane next to the stapes to move, whereas the sounds with low frequencies almost cause movements through the entire membrane. The location that is closest to the apex experiences the optimum displacement. This implication here is that the raveling always moves from the base to the apex. When placed under physiological circumstances, the stimulus that drives the basilar membrane tends to be the distributed pressure. It is purely derived from the incoming sound waves. Compared to the stiffness of the basilar membrane measurements the stimulus becomes the force focal point it is then applied to a position that is radial to the basilar membrane. The trend of change of the ratio of the external to the internal radius amplitude remains unchanged. This happens irrespective of the high frequencies that seem to influence the basilar membrane at the different points of curvature. Fig(3) is an illustration of such a tendency.[5] ,[7]

Fig. 3: The ratio of the basilar membrane horizontal amplitude and the frequencies displacement



Inner-ear fluid Mechanics

Inner-ear fluid mechanics involves the 'semicircular canals'. These canals are contained in the vestibular systems. The fluid in the cochlea surrounding the basilar membrane is incompressible, and assumed to be inviscid. Therefore, the equations of motion of this fluid follow the mode of these two assumptions. If the fluid velocity in the 3D is : $U = (u_1, u_2, u_3)$, the pressure and the density are p_1 and ρ_1 respectively, the mass of fluid in a fixed volume V changes only in response to fluid flux across the boundary of the volume, then :

$$\frac{d}{dt}\int_V \rho_1\, dV = -\int_S \rho_1 (U.\boldsymbol{n})\, dS \quad , \quad (17)$$

where S represents the surface of V, and **n** = $(n_1, n_2,\ n_3)$ is the outward unit normal to V , on the other hand, the momentum of the fluid in a fixed domain V changes only in response to applied forces or to the flux of momentum across the boundary of the domain. Since the fluid is inviscid, we can apply the role of momentum conservation as:

$$\frac{d}{dt}\int_s \rho_1\, u_i\, dV = -\int_S [(U.\boldsymbol{n})\rho_1 u_i + p n_i]\, dS \quad , \quad (18)$$

By converting the surface integrals to volume integrals, equation (18) yields:

$$\int_V \left(\frac{\partial \rho_1 u_i}{\partial t} + \rho_1 \nabla.(u_i U) + \frac{\partial p}{\partial u_i}\right) dV = 0 \quad , \quad (19)$$

$$\int_V \frac{\partial \rho_1}{\partial t} + \nabla.\mathrm{U dV} = 0 \quad , \quad (20)$$

V is an arbitrary parameter and ρ_1 is constant this leads to:

$$\rho_1 \frac{\partial U}{\partial t} + \rho_1 (\nabla.U)U + \nabla p = 0 \quad , \quad (21)$$

$$\nabla.U = 0 \quad , \quad (22)$$

Because the motions of the cochlear fluid are of small amplitude, as expected, the nonlinear terms are ignored yielding:

$$\rho_1 \frac{\partial U}{\partial t} + \nabla p = 0 \quad , \quad (23)$$

$$\nabla . U = 0 \quad , \quad (24)$$

If the fluid flow is irrotational, this is a special case where the velocity field $U = \nabla \emptyset$ and equations (23),(24) become :

$$\rho_1 \frac{\partial \emptyset}{\partial t} + p = 0 \quad , \quad (25)$$

$$\nabla^2 \emptyset = 0 \quad , \quad (26)$$

The basilar membrane always deflects bundles of hair that are mechanically sensitive in the sensory receptor. As the mechanical sensory ion channels close and open, the hair bundle cells respond with the elective signal. The elective signal is chemically transmitted which directs the nerve fiber into the brain. Additionally, the inputs that are mechanically transduced are amplified into hair cells. The endowment of channel gating a hair bundle with instability and negative stiffness to interact with the motor myosin protein to release mechanical oscillator and amplifier. The responses about electricity cause the outer hairy cells to shorten thus pumping the energy into the movement of the basilar membrane. Most important to note is that the two motility forms allow the active process to amplify mechanical inputs, frequency discrimination, sharpens, and compares the nonlinearity on responsiveness. Such items increase because the active process works alongside a Hopf bifurcation, thus the generic elements explain characteristics of hearing. [9], [6]

Influence of the inner inner-ear fluid on the basilar membrane frequenters.

The sensory cells located along the basilar membrane in the Corti organ are flexible along the whole cochlea. The sensation of the high-frequency sound and stimulation of the sensory cells situated at the cochlear apex causes the low-frequency sound of the sensation. The organization of the cochlea is partly maintained within the central processing of auditory stimuli. The process of sensory is protected by the basic feedback mechanisms that contain the inner ear that terminate on the efferent nerves along with the sensory cells. [14],[1]

The cochlear partition divides the cochlea that is in a dynamic structure that protects both the basilar membrane and the tectorial membrane. There are spaces filled with the fluid on all sides is the cochlear partition known as the Scala vestibule and the Scala tympana which are a distinct channel, The Scala media then moves all over the cochlear partition. There is an opening called the helicotrema that combines the Scala vestibule and the Scala tympani.

However, the cochlear partition does not reach to the apical end of the cochlea. Due to this structural organization, the internal movement of the oval window removes the inner ear fluid that leads to the bulge out of the round window and deforms the basilar membrane.[15]

Also, the deflection of the basilar membrane is compared to inner ear sensitivity. The research concludes that the bony structure shape around the three tubes is less essential. By way of comparison, the inner ear mechanics is highly affected by the Reissener's membrane though it is too small. It indicated that the membrane contributes much to the cochlea's better frequency selectivity.

How the Basilar membrane vibrates after the sound is one explanation to the functioning of the cochlear. The vibration measurements of the several parts of the basilar membrane together with the discharge rates of the auditory nerve fibers of an individual indicate that these characteristics are both tuned highly. This implies they only respond to a particular frequency sound. The tuning of the frequency in the inner ear is brought about by the basilar membrane geometry that is bigger, more flexible at the apical end, and narrower, stiffer towards the basal end. The basic feature of such a situation is that movement usually starts at the stiff end and then moves towards the flexible side without considering where energy is supplied). Basing on the research made by Georg von Békésy from Harvard University indicated that a membrane that changes in width and flexibility vibrates in different parts as a frequency stimulus function. By application of the 'tabular models and the human cochlea's' retrieved from cadavers, he discovered that an acoustical stimulus provides a traveling wave of the particular frequency within the cochlea. This emanates from the initial point rising upwards to the apex of the 'basilar membrane' growing in size and retarding in velocity. The maximal point of displacement is determined by the sound frequency. The points reflecting the higher frequencies are located along the base of the basilar membrane well as the points reflecting the low frequencies are located at the apex. This produces a frequency that is called 'topographical mapping' (Kim & Koo, 2015). Complex sounds causing a vibration pattern similar to the deposition of the vibration created by the individual sounds leading to a bigger sound is an essential and striking feature of the 'tonotopically-arranged' basilar membrane. This brings about the decomposition of the cochlear function within the inner ear. [1]

The traveling wave motion brings about sensory transduction by removing the hair cells that are located on top of the basilar membrane. Since the structures are located in different places, the vertical component of the traveling wave changes into a shearing motion between the basilar membrane and the overlying tectorial membrane. It then bends the small processes known as the stereocilia that move from the apical ends of the hair cells causing the voltage to change the hair cell membrane.

In the cochlea, the various complex sound frequencies are selected or analyzed and later there is the conversion of physical energy sound vibrations into electrical impulses. These impulses then transfer via the cochlear nerve to the brainstem. The cochlea analyzes the sound waves into a distinguished pitch through the basilar membrane that has several stiffness degrees or resonance around its length. The fluid movement within the inner ear forces the thin hair in the cochlea to bend of which the bending hair in the fluid turns the sound waves into the electrical signals. The auditory nerves transfer the electrical signals directly to the brain via the fluid known as the lymphatic fluid fills the surroundings and the entire membrane. This fluid contains more sodium but with less potassium. [11],[4]

Conclusion

The inner ear fluid on the three-dimensional models has various influences on the general functioning of the basilar membrane mechanics and frequencies as well as the ear. The analysis urges that the sounds with high frequencies can only cause the basilar membrane next to the stapes to move, whereas the sounds with low frequencies almost cause movements through the entire membrane .Therefore, the brain shows the direction in which the head should be rotated by the total vector of the inputs of the semicircular canals. Thus, resulting in angular motion perception. Additionally, the velocity perception signals allow the eye movement to compensate with the head movement to maintain the focus and balance while moving. Most significantly, minuscule bones in the inner ear act as the piston to officiate oscillatory changes of pressure with liquid in the cochlea, the former influence the basilar membranes mechanics and frequencies movement.

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References

1-Ciuman, R.R. (2013). Inner ear symptoms and disease: Pathophysiological understanding and therapeutic options. Retrieved from:

2-De Paolis, A., Bikson, M., Nelson, J., T., Alexander, J., Packer, M., Cardoso, L. (2017). Analytical And Numerical Modeling Of The Hearing System: Advances Towards The Assessment Of Hearing Damage. Vol. 349, Pp: 111-128.

3-Hernandez, J., M. (2017). Power Analysis Of The Basilar Membrane In The Cochlear By Mechanical Resonance. Vol. 38, Issue 1. Pp: 38-53.

4-Kim, J & Koo, M. (2015). Mass and Stiffness Impact on the Middle Ear and the Cochlear Partition. Retrieved from

5-Kwacz, M., Borkowski, P., Marek, P., Mrowka, M. (2014). A Three-Dimensional Finite Element Model Of Round Window Membrane Vibration Before And After Stapedotomy: Biomechanics And Modeling In Mechanobiology.

6-Martignoli, S., van der Vyver, J.-J., Kern, A., Uwate, Y. & Stoop, R. (2017). Analog electronic cochlea with mammalian hearing characteristics. *Applied Physics Letters* 91 (064108).

7-Marxen, M., Sullivan, P. E., Loewen, M. R. &Jahne, B. (2010). Comparison of Gaussian particle center estimators and the achievable measurement density for particle tracking velocimetry. Exp. Fluids 29 (2), 145–153

8-Meaud, J., Grosh, K.(2010). The Effect Of Tectorial Membrane And Basilar Longitudinal Coupling In Cochlear Mechanics: The Journal Of Acoustical Society Of America. Retrieve from

9-Nakajima, H., Dong, W., Olson, E., Merchant, S., Ravicz, M. &Rosowski, J. (2009). Differential intracochlear sound pressure measurements in normal human temporal bones. JARO 10, 23–36, retrieved from: 10.1007/s10162-008-0150-y

10-Ni, G., Elliot, S., J., Teal, P. (2014). Modeling Cochlear Mechanics. Retrieved from

11-Reichenbach, T & Hudspeth. A.J (2012). The physics of hearing: fluid mechanics and the active process of the inner ear. Retrieved from:

12.Tang, Z., Shen, Q., Xu, C., Wang, Q., Liu, Zh., Li, Sj. (2016). Research On The Characteristics Of Dynamic Behavior Of Basilar Membrane In Spiral Cochlea. Vol, 19, Issue 5, Pp: 3809-3821.

13.Teudt, I., U., Ritcher, C., P. (2014). Basilar Membrane And Tectorial Membrane Stiffness In The CBA/Caj.

14.Yao, W. Chen, Y. Ma, J. Gan, C. & Wang, J. (2016).Numerical simulation on the dynamic behavior of the basilar membrane in the spiral cochlea. *Biomedical Research*. Volume 27, Issue 3.

15.Zdebik, A.A, Wangemann, P &Jentsch, J.T. (2015). Potassium Ion Movement in the Inner Ear: Insights from Genetic Disease and Mouse Models. Retrieved from: