Simulating and investigating the effect of surgical opening of cochlea on the cochlear travelling wave.

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by

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GUIDE CERTIFICATION

This is to certify that the report titled “Simulating and investigating the effect of surgical opening of cochlea on the cochlear travelling wave” submitted by LAKAVATH SANTHOSH (Roll No: 234103326) to the Department of Mechanical Engineering, Indian Institute of Technology Guwahati,Assam, has been done under my supervision.
In order to partially complete the requirements for the current semester's Master of Technology project, we recommend submitting this report.

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ABSTRACT

The cochlea, a spiral-shaped organ in the inner ear, is vital for hearing, as it converts sound vibrations into neural signals that the brain can process. This process depends heavily on the traveling wave phenomenon along the basilar membrane, where different frequencies are detected at specific locations. However, surgical procedures, such as those performed for cochlear implantations, can disrupt the natural mechanics of the cochlea, potentially affecting its ability to process sound. Understanding how surgical openings impact the traveling wave is essential for improving surgical outcomes and developing better hearing restoration techniques.

This study focuses on investigating the effects of surgical openings in the cochlea on the propagation of traveling waves. Using insights from existing research and simulations, this work explores how factors such as the size and location of these openings influence the amplitude and movement of the basilar membrane. By analyzing these effects, the study aims to shed light on the biomechanical changes caused by surgical interventions.

Preliminary findings suggest that surgical openings can lead to significant disruptions in the normal function of the cochlea, altering the wave patterns and potentially affecting the cochlear tuning that is essential for frequency discrimination. These results highlight the need for careful surgical planning and provide a foundation for future work, where more advanced models will be developed to simulate cochlear mechanics in greater detail.

This research contributes to a better understanding of cochlear mechanics and paves the way for innovations in surgical techniques and hearing restoration technologies. The insights gained here are particularly valuable for improving outcomes in cochlear implant surgeries and ensuring minimal disruption to the natural processes of hearing.

CHAPTER 1
INTRODUCTION

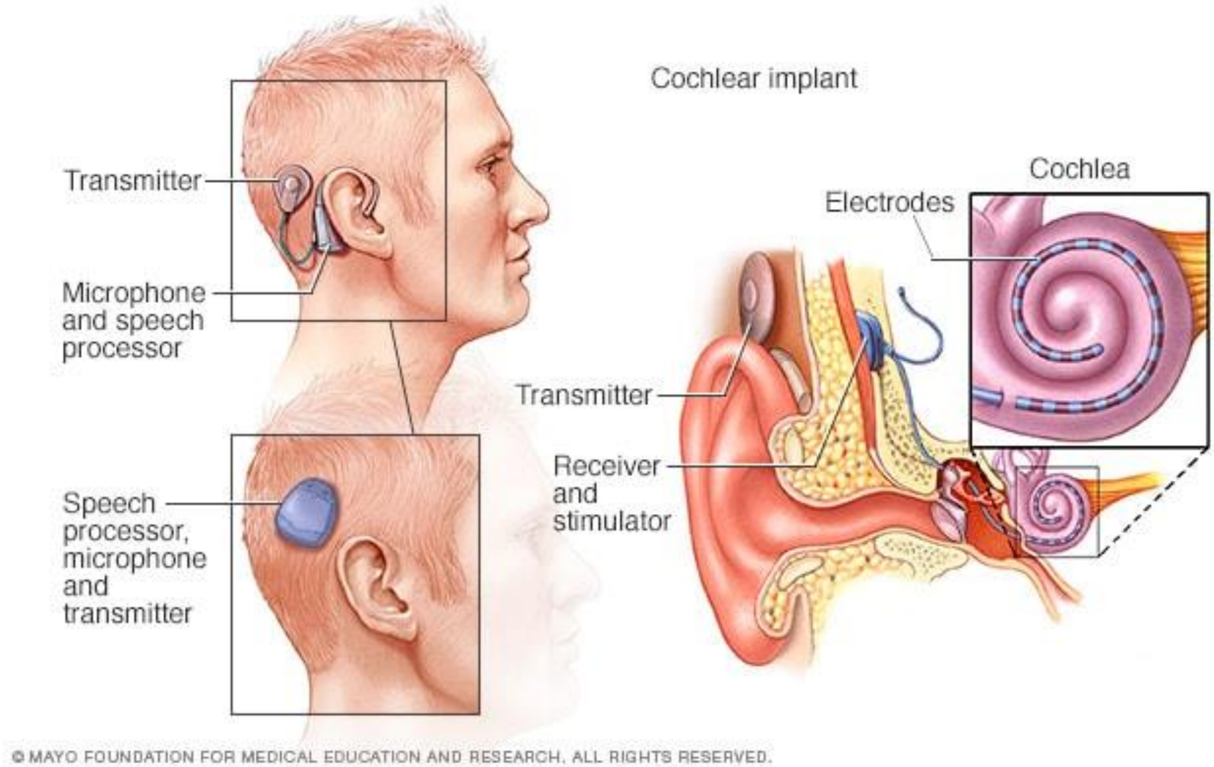

Figure 1.1: Cochlear Implant [1] Source:Mayo clinic

Hearing loss is one of the most common disabilities people face worldwide, affecting millions of individuals. Whether it’s from aging, prolonged exposure to loud noises, or genetic conditions, hearing loss can have a profound impact on daily life. For many, hearing aids provide a solution, but for those with severe or profound hearing loss, traditional hearing aids don’t always work because they just amplify sound without addressing the actual problem. In these cases, cochlear implants offer a revolutionary solution. These implants can restore some level of hearing by bypassing the damaged parts of the ear and directly stimulating the auditory nerve, which sends signals to the brain.

Why Cochlear Implant Surgery is Necessary

Cochlear implants are designed for individuals who suffer from severe sensorineural hearing loss, where the cochlea the organ in the inner ear responsible for turning sound into electrical signals is damaged. In a healthy ear, sound waves travel through the outer ear, vibrate the eardrum, and are transmitted to the cochlea, where they’re turned into electrical signals by hair cells. These signals are then sent to the brain via the auditory nerve. However, in those with profound hearing loss, the hair cells of the cochlea are often damaged or nonfunctional.While the auditory nerve

may still be intact, it no longer receives the signals it needs to perceive sound.
The cochlear implant works by bypassing the damaged hair cells altogether. Instead, it uses an electrode array surgically inserted into the cochlea to directly stimulate the auditory nerve, allowing individuals to hear. This technology has been transformative, allowing many individuals with severe hearing loss to regain partial or even full hearing. But, while cochlear implants have improved the lives of many, the process of implanting the device is not without challenges.

The Challenges and Limitations of Cochlear Implant Surgery

Despite the success of cochlear implants, the surgery required to insert the device carries its own set of challenges. The cochlea is a small, delicate, and spiral-shaped structure located deep inside the ear. During surgery, an electrode array is inserted into the cochlea through a small opening. This procedure requires great precision, as any misstep can result in additional damage to the cochlea's already fragile structures. The surgical opening itself can disrupt the cochlea's natural fluid dynamics, which are crucial for the proper functioning of the cochlea.
One of the most critical issues to address is the disturbance to the cochlear traveling wave—the movement of fluid in the cochlea that is essential for distinguishing between different sound frequencies. When the cochlea's natural fluid movement is disturbed, it can affect the cochlear response to sound. This can lead to a decreased ability to discern specific frequencies or even result in poor sound quality, which undermines the purpose of the cochlear implant.
Another limitation of the procedure is the potential for surgical deformities that can occur during the implantation. These deformities can arise due to factors like incorrect placement of the electrode, excessive force applied during insertion, or unintentional damage to the cochlea. Such deformities could alter the shape and function of the cochlea, particularly affecting how the traveling wave propagates along the basilar membrane. Any alteration to the normal flow of fluid within the cochlea can result in a suboptimal response to sound, potentially affecting the overall effectiveness of the implant.

Understanding the Human Ear: Anatomy and Function

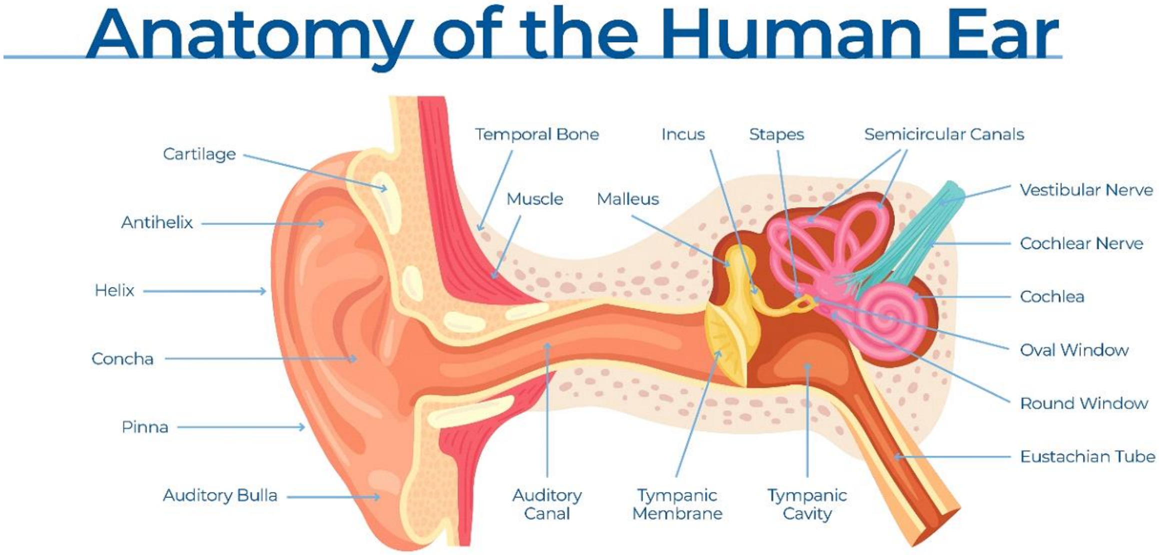

Figure 1.2: Anatomy of human ear [2] Source:Mayo clinic

To understand why these disruptions are important, it’s crucial to first understand how the human ear works. The ear is made up of three parts: the outer ear, middle ear, and inner ear. The outer ear collects sound, and the sound waves travel through the ear canal to vibrate the eardrum. These vibrations are then transmitted through the small bones in the middle ear—the malleus, incus, and stapes toward the inner ear.

The inner ear contains the cochlea, a fluid-filled spiral that plays a key role in hearing. The cochlea is home to the basilar membrane, which vibrates in response to sound. As sound travels through the cochlea, it creates a traveling wave along the membrane. This wave helps the cochlea discriminate between different sound frequencies: high-frequency sounds create a wave at the base of the cochlea, while low-frequency sounds peak closer to the apex. This separation is crucial for us to perceive and understand speech, music, and other sounds in our environment.

The movement of the basilar membrane is detected by hair cells, which convert the mechanical movement into electrical signals. These signals are sent to the brain, where they are interpreted as sound. This finely tuned process of sound detection is essential for us to communicate and navigate the world around us. But when the cochlea is damaged, this process is disrupted, and the brain can no longer interpret sound correctly.

The Traveling Wave and Its Significance in Cochlear Function

The cochlear traveling wave is a key component in the process of hearing. It allows the cochlea to effectively separate different sound frequencies, something that is vital for speech comprehension and sound clarity. The wave travels through the cochlea’s fluid chambers and peaks at different points depending on the frequency of the sound. Disruptions in the propagation of this wave whether from surgery or other causes can interfere with the cochlea’s ability to accurately analyze sound.

When a cochlear implant is inserted, the electrode array disturbs the cochlea’s natural fluid dynamics, which can change how the traveling wave behaves. If the traveling wave is disrupted or altered, it may not properly reach the areas of the cochlea that respond to particular frequencies. This means that even though the patient may hear sounds through the implant, they might not be able to hear them clearly or with the same level of detail as before. In fact, many individuals with cochlear implants experience difficulty with distinguishing high-frequency sounds or complex speech patterns, which may be related to these disruptions.

Surgical Deformities and Their Impact on Cochlear Function

Surgical deformities are another critical aspect that can negatively affect the cochlea’s function. These deformities might not be immediately noticeable after the procedure, but over time, they can lead to further complications. For example, if the insertion of the electrode array causes changes in the shape of the cochlear duct or damage to the cochlear membranes, it can alter the way the cochlea processes sound. In some cases, such deformations may even exacerbate the natural degradation of hearing that occurs due to age or other factors.

When surgical deformities occur, they can create lasting changes in the cochlea’s structure, which can, in turn, affect the traveling wave’s propagation. This may alter the patient’s hearing experience, making it harder for them to perceive specific sounds or distinguish between them. The severity of these issues can vary depending on the nature of the deformity, the extent of the surgical procedure, and the individual’s response to the implantation.

MOTIVATION OF THE STUDY

As many as 1.5 billion or 20% of the world population is known to suffer from some degree of hearing loss, and the numbers are projected to grow to 2.5 billion by 2050. Among them, not less than 163 million (2.1% of world population) suffer from moderately severe to complete hearing loss. The graphical representation of people suffering from various grades of hearing loss is shown below:

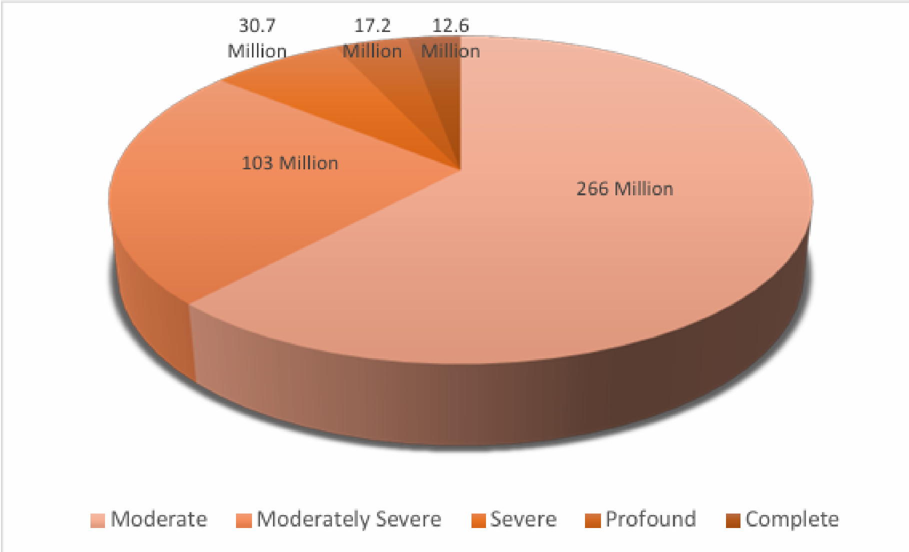

Figure 1.3: Population distribution of people suffering from various degrees of hearing loss (source: United Nation Hearing Report)

Moreover, the South-East Asian Region alone has a population of 109 million living with moderate to complete hearing loss. In India, hearing loss is 2nd most common form of disability.A total of 19% of the total 2.68 crore of total disable population of India suffer from hearing impairment.While mild and moderate hearing loss can be treated with the use of an external hearing aid, other grades of hearing loss arising out of sensorineural dysfunction require cochlear implantation. In developing countries, children with hearing loss and deafness often do not receive schooling. The unemployment rate among adults with hearing loss is also very high. With those who are employed, people with hearing loss suffer from disparity in terms of wages and position. Hearing aids and implants have the power to bridge the gap for people with hearing disabilities. In its report "World Report on Hearing," WHO has recently recognized the growing trend in hearing loss and has shown concerns over the increase of unsafe hearing environments. With the increasing number of people with hearing loss, cochlear implantation is the sought after solution.

Cochlear implants have proven to be life-changing for many, allowing recipients to regain a sense of hearing and improve their quality of life. Yet, challenges remain in optimizing the implantation process and understanding its full impact on cochlear function. In particular, the potential for disruption to the cochlea's natural fluid dynamics especially the traveling wave mechanism during implantation raises concerns about the long-term efficacy and outcomes of the procedure.

The traveling wave within the cochlea plays a vital role in the processing of sound, allowing for the accurate representation of different frequencies. The cochlear traveling wave's ability to propagate along the basilar membrane is essential for normal hearing. Any surgical intervention, including the insertion of the cochlear implant electrode array, may disrupt this delicate fluid wave and impact how sound signals are transmitted and processed. Similarly, the surgical opening of the cochlea and punctures made in the oval or round windows during implantation may lead to additional disturbances in the fluid dynamics, further affecting cochlear function.

Moreover, the effectiveness of cochlear implants in restoring hearing is not uniform across all patients. Variations in surgical technique, electrode positioning, and individual anatomical differences can lead to discrepancies in the performance of cochlear implants. The spread of electrical stimulation within the cochlea and its effect on the traveling wave are believed to play a crucial role in the variability of speech perception outcomes among CI users. As a result, it is essential to better understand the mechanical and physiological consequences of cochlear implant surgery, particularly with regard to how it alters the cochlear traveling wave.

This study is motivated by the need to investigate and quantify the disturbances caused by the surgical opening of the cochlea, the insertion of the electrode array, and the punctures in the oval and round windows. By simulating these effects on the cochlear traveling wave, we aim to gain a deeper understanding of how the surgical process impacts cochlear function. Understanding the disturbances in the traveling wave will provide valuable insights into optimizing the implantation procedure, improving electrode design, and enhancing patient outcomes. Furthermore, identifying potential surgical deformities that affect cochlear fluid dynamics can lead to better surgical practices and techniques, minimizing the risk of complications and improving the overall success of cochlear implants.

The motivation behind this research is not only to understand the immediate effects of surgery on cochlear function but also to explore how these disturbances may impact long-term hearing outcomes. By modeling the biomechanical effects of surgical interventions on the cochlea, this study aims to contribute to the development of more effective, minimally invasive cochlear implant procedures that preserve cochlear integrity and enhance the auditory experience for patients. Ultimately, the findings from this study could pave the way for improvements in cochlear implant technology and surgical practices, ensuring better hearing outcomes for patients and improving their integration into society.

CHAPTER 2
LITERATURE REVIEW

The cochlea,a highly specialized sensory organ, converts sound vibrations into neural signals via the mechanical oscillations of its basilar membrane, which propagates a traveling wave. The cochlear traveling wave is critical for the cochlea's frequency selectivity, whereby different regions of the basilar membrane respond to different frequencies of sound. However, various medical interventions, particularly cochlear implant insertions and surgical openings such as round and oval window punctures, can significantly disrupt the fluid dynamics and mechanical response of the cochlea. These disturbances affect the traveling wave, influencing hearing preservation and implant performance. This review examines the key disturbances to the cochlear traveling wave resulting from these procedures, with an emphasis on the mechanical and fluid-structure interactions, and their impact on cochlear function and hearing outcomes.

1. Introduction to Cochlear Function and Traveling Wave Dynamics:

The cochlea plays a fundamental role in auditory perception, transforming mechanical vibrations into neural signals through a highly specialized process involving the traveling wave. Pioneering research by G.V.Békésy[1] laid the groundwork for understanding cochlear mechanics. His experiments using excised cochleae revealed that sound waves generate a traveling wave along the basilar membrane (BM),with its peak amplitude corresponding to the sound frequency. This peak location defines cochlear tonotopy a spatial encoding of frequencies crucial for auditory processing.

D.D.Greenwood[2] further developed the frequency-position relationship, deriving a mathematical function to map frequencies to their corresponding BM locations. This mapping has been widely used in auditory modeling and clinical applications, especially in cochlear implant (CI) programming. Subsequent studies (S.Iurato: G.Ehret et.al)[3],[4] expanded on Bekesy's findings, demonstrating that the stiffness gradient along the BM plays a pivotal role in determining the traveling wave's propagation and frequency selectivity.

The traveling wave's importance lies in its ability to activate specific hair cells within the organ of Corti, converting mechanical energy into electrical signals. J.H.Nam and R.Fettiplace et.al[5] highlighted the intricate force transmission mechanisms within the organ of Corti,where BM vibrations are amplified and transmitted to hair cells via the tectorial membrane.These processes are central to cochlear function and underpin the auditory system's high sensitivity and dynamic range.

2. Structural and Mechanical Properties of Cochlear Components

The cochlea's ability to encode sound frequencies is intricately linked to the mechanical properties of its structures. The BM, with its graded stiffness from base to apex, acts as a frequency-selective filter. S.Liu and R.D.White et.al[6] characterized the BM as an orthotropic material, highlighting its directionally dependent mechanical properties.This anisotropy ensures efficient traveling wave propagation while maintaining structural integrity under dynamic loading.

The cochlear fluids, perilymph and endolymph, provide essential coupling between the BM and cochlear walls. X.Zhang and R.Z.Gan[7] studied the dynamic properties of the round window membrane(RWM), which mediates pressure changes within the cochlea. Their findings emphasized the importance of RWM compliance in maintaining fluid motion and wave transmission, particularly in pathological or surgically altered cochleae.

Mathematical and computational modeling has significantly advanced our understanding of cochlear mechanics. D.Trippett[8] foundational theories provided the basis for early mathematical models of sound wave propagation.D.D.Greenwood[2] frequency-position function remains a cornerstone for cochlear modeling, offering insights into BM mechanics and tonotopy.

Finite element modeling (FEM) has emerged as a powerful tool for simulating cochlear responses to sound and surgical interventions. R.Z.Gan[9] developed a three-dimensional FEM of the human ear, incorporating cochlear fluid dynamics, BM properties, and ossicular motion. M.Kwacz[10] applied FEM to study RWM vibrations before and after stapedotomy surgery, demonstrating how surgical modifications alter BM motion and fluid flow.

S.J.Elliott[11]introduced an elemental approach to modeling cochlear mechanics, integrating stiffness, damping, and fluid-structure interactions. These models have been pivotal in predicting cochlear responses to complex stimuli and evaluating surgical impacts.

Disruptions to the traveling wave, whether due to pathology or surgical intervention, can significantly impair auditory function.Stenfelt [12] measured BM motion in cadaveric cochleae, revealing that air- and bone-conducted stimuli produce distinct wave patterns. These findings provided insights into the effects of mechanical alterations on cochlear function.

Surgical procedures, such as cochleostomy and electrode insertion, introduce mechanical disturbances that affect wave propagation.Gstoettner[13] studied the trauma caused by deep electrode insertion,finding significant disruption to BM mechanics.Kwacz[14] emphasized the importance of preserving cochlear structures during CI surgery to minimize these disturbances.

Cochlear implants are transformative for individuals with severe hearing loss, yet their insertion can disrupt the cochlear microenvironment.Stenfelt,Gstoettner et.al[15]and[16]investigated techniques for hearing preservation during CI surgery, focusing on electrode design and insertion methods.Gstoettner[15] modeled the effects of RWM stiffness changes post-surgery, showing that increased stiffness disrupts traveling wave dynamics. These findings underscore the need for atraumatic surgical techniques to optimize hearing outcomes.

The RWM is a critical structure for cochlear fluid dynamics and traveling wave propagation.Kwacz[14]reviewed its anatomical and functional significance, highlighting its role in pressure equalization and expanded on this, demonstrating how changes in RWM compliance affect cochlear function.

Kwacz[14] used FEM to study RWM behavior under different surgical scenarios, showing how modifications to its stiffness or shape alter wave propagation. These studies are vital for understanding the implications of CI surgery and other interventions on cochlear mechanics.

Energy flow analysis provides insights into how mechanical energy propagates and dissipates within the cochlea.Y.Wang[17] reviewed energy flow methods, including volume energy flow and the energy finite element method, as applied to vibrating structures.G.Ehret[18] used these principles to model cochlear energy transfer, focusing on fluid-structure interactions and BM vibrations.

Kwacz,Stenfelt et.al[16] and [14] demonstrated how vibrational energy patterns change with surgical modifications, providing a framework for assessing the impact of cochleostomy and electrode insertion on auditory function.

8. Surgical Interventions and Cochlear Modifications

Surgical interventions often alter the cochlea's mechanical properties, leading to changes in traveling wave behavior.R.Z.Gan,Kwacz et.al[19]and[14]demonstrated how cochleostomy and stapedotomy surgeries affect fluid dynamics and BM motion. These studies emphasize the need for precise surgical techniques to minimize disruptions.

The long-term effects of surgical modifications on cochlear mechanics remain an area of active research.X.Zhang and R.Z.Gan [20]studied the dynamic properties of the RWM post-surgery, highlighting the importance of preserving its compliance to maintain cochlear function.

The velocity and amplitude of the traveling wave are influenced by several factors, including the mechanical properties of the basilar membrane and the fluid environment in which the wave propagates G.Ehret,Greenwood et.al[18];[2]. Any mechanical or fluid disturbance can lead to alterations in wave propagation, including shifts in frequency tuning, reduced amplitude, or phase misalignment. The following are key parameters that impact traveling wave dynamics:

The basilar membrane's stiffness decreases gradually from the base to the apex, contributing to the tonotopic organization of the cochlea Elliott[21]. This gradient is crucial for the separation of frequencies, and any changes to it whether due to implantation or injury can distort frequency representation.

The cochlear fluid's viscosity affects the traveling wave's attenuation and energy dissipation. Increased viscosity, which can result from inflammatory processes or surgical interventions, may lead to an increased damping of the wave, reducing its amplitude and affecting the cochlea's frequency selectivity R.Z.Gan[19].

The shape and size of cochlear structures, such as the cochlear duct, basilar membrane, and spiral lamina, contribute to the propagation characteristics of the traveling wave. Structural modifications caused by surgery can alter these properties and disturb normal wave transmission Stenfelt[16].

One of the primary disturbances caused by cochlear implant insertion is the mechanical interaction between the electrode array and the cochlear structures. Flexible electrode arrays, such as the FLEXsoft array, are designed to reduce mechanical trauma by conforming to the cochlear anatomy. However, even these flexible electrodes introduce stiffness to the cochlea and alter the wave transmission. The electrode array may restrict the basilar membrane's movement, leading to reduced wave amplitude and incomplete wave propagation Trippett[8].

Studies by Ehret[18]showed that while flexible electrodes reduce trauma compared to rigid ones, they still interfere with the natural fluid-structure interactions, causing attenuation of the traveling wave. The result is a degradation of the cochlea's frequency resolution, particularly in higher-frequency regions.

The insertion of the electrode array into the cochlea can disturb the fluid pressure in the scala tympani and scala vestibuli, which are responsible for supporting the propagation of the traveling wave. The electrode array may obstruct fluid flow, creating local pressure gradients that distort the traveling wave. R.Z.Gan[19] demonstrated that such disturbances could lead to an uneven pressure distribution within the cochlear fluid, resulting in incomplete or altered waveforms.

The depth of electrode insertion is a critical factor influencing wave propagation. Deeper electrode insertions can cause greater mechanical trauma and disruption to cochlear mechanics Gstoettner[15]. The deeper the electrode, the greater the likelihood of disrupting the natural traveling wave, particularly in the apical regions of the cochlea.White[22] observed that deep insertion of the electrode array exacerbates the attenuation of low-frequency signals, leading to poorer hearing outcomes in patients.

The round window puncture alters the mechanical properties of the cochlear fluid and reduces its ability to dissipate excess pressure. This loss of pressure regulation results in increased wave reflection, leading to reduced transmission efficiency and distortion of the traveling wave Fettiplace[23]. This phenomenon has been shown to attenuate high-frequency components and can result in poor hearing outcomes following surgery.

R.D.Fettiplace[23] also highlighted that the round window puncture interferes with the tonotopic organization of the cochlea. The interruption of normal fluid motion causes misalignment of phase relations along the basilar membrane, further distorting the traveling wave and reducing the cochlea's ability to accurately represent sound frequencies. As a result, cochlear implants may fail to provide the desired hearing restoration, especially for high-frequency sounds.

The oval window puncture leads to a loss of mechanical coupling between the middle ear and the cochlea, increasing the potential for fluid backflow. This disruption in fluid motion may cause interference with the traveling wave, especially in the basal regions where higher frequencies are typically processed. The altered pressure distribution resulting from oval window puncture leads to increased phase shift and wave attenuationWhite[22].

Puncturing the oval window can cause mechanical trauma to the cochlea, including damage to the stapes or cochlear structures near the oval window. This trauma can lead to scarring or inflammation that further disturbs the fluid pressure wave and compromises wave propagationGstoettner[15]. In some cases, the damage may lead to permanent loss of residual hearing.

Fluid Dynamics Disturbances:

The fluid dynamics in the cochlea, specifically the pressure waves in the perilymph and endolymph, are critical in the functioning of the traveling wave. When an electrode is inserted into the cochlea, it can block or distort the natural flow of these fluids, altering the pressure gradients within the cochlea. The presence of the electrode array disturbs the natural fluid circulation, resulting in localized fluid pressure changes that affect the traveling wave.

Elliott[21] provided a theoretical framework based on finite element models that explored how the insertion of the electrode into the cochlea affected the fluid pressure wave in the perilymph. Their results suggested that a rigid electrode array blocks the natural fluid flow, leading to uneven fluid pressure distributions, especially near the round window and basal turn of the cochlea. This results in phase distortion in the traveling wave, as the pressure wave interacts with the electrode and the cochlear wall.

Similarly, X.Zhang and R.Z.Gan et.al[20] conducted studies on the dynamic properties of the round window membrane (RWM) and how it responds to sound pressure waves. They found that the insertion of an electrode modifies the fluid-structure interaction at the RWM, altering the transmission of fluid pressure to the basilar membrane. The electrode disrupts the fluid continuity, which leads to attenuation and phase shifts in the traveling wave, particularly in the high-frequency regions.

CHAPTER 3
RESEARCH GAP

• The current literature predominantly focuses on the mechanical and fluid dynamics of the cochlea, but lacks detailed modeling of how surgical interventions, such as round and oval window punctures or cochlear implant insertions, disrupt the traveling wave propagation and cochlear fluid mechanics.

• Although many studies have used simplified models to simulate cochlear responses, there is no robust, comprehensive finite element model that incorporates both the complex fluid-structure interactions and mechanical disturbances caused by surgical openings or electrode insertions.

• Existing research primarily addresses the effects of the electrode array on cochlear mechanics, but does not fully explore the combined impact of surgical openings and electrode insertions on the cochlear traveling wave, particularly in terms of frequency selectivity and wave amplitude attenuation.

• No studies have developed models that simulate the long-term effects of these surgical interventions on cochlear mechanics, particularly how changes in RWM compliance, electrode depth, and oval/round window punctures influence wave dynamics and residual hearing preservation.

• Many studies focus on the effects of cochlear implantation on BM motion, but there is a lack of investigation into the dynamic interactions between the cochlear fluids, electrode array, and BM, particularly under varying surgical conditions and in a post-surgical cochlear environment.

• Most cochlear models fail to account for the non-linear and time-varying nature of the cochlear system, especially after surgical alterations, leading to oversimplified assumptions that may not accurately predict real-world outcomes for hearing preservation and implant efficacy.

• The current body of research lacks a detailed, multi-scale model that integrates both the mechanical and biochemical changes occurring due to surgical interventions, limiting its applicability for improving cochlear implant techniques and outcomes.

CHAPTER 4
PROPOSED OBJECTIVE

The primary objective of the study is to focus on the disturbances caused to the cochlear travelling wave by the cochlear implant insertion and surgical punctures in the Round and Oval windows.

In order to achieve this, the following sub-objectives are formulated:

1. To study the Cochlear travelling wave inside a healthier cochlea model using Finite Element Method (FEM).
2. To analyze the effects of electrode insertion on the basilar membrane displacement and its impact on traveling wave propagation across different frequencies.
3. To investigate how round and oval window punctures alter fluid pressure and disrupt cochlear wave dynamics, considering the resulting changes in cochlear fluid interaction.

CHAPTER 5
METHODOLOGY

The objective of this methodology is to explain the process of developing a 3D CAD model of the cochlea using SolidWorks software. This model represents the cochlear structure in a simplified form,taking into account the basic anatomical components and properties needed for future simulations (such as FEA and ANSYS Fluent), but focusing on the geometrical representation of the cochlea for now.

The cochlea model was created based on a simplified version of the cochlear anatomy, inspired by various literature and studies on the human cochlea. In the following sections, the step-by-step approach for constructing the model, including dimensions, material properties, assumptions, and the software usage is described.

1. Modeling the Cochlea: Geometry and Components

The cochlea in its natural state has a highly complex three-dimensional spiral structure, making it difficult to model in its entirety. To manage the complexity, a simplified box model of the cochlea was chosen, which was constructed using SolidWorks. The major parts of the cochlea were modeled based on the components necessary for fluid-structure interaction analysis and the propagation of sound-induced fluid waves.

Cochlea Wall: The cochlear wall forms the external boundary, supporting the internal structures. It was modeled to simulate the outer shell and its interaction with the basilar membrane.

Oval Window: The oval window is where sound vibrations from the middle ear are transmitted into the cochlear fluid. It is located at the entrance of the cochlea. For this model, the oval window was modeled as a circular hole on the cochlea wall where the vibrations from the stapes are introduced.

Round Window: Positioned at the base of the cochlea, the round window plays a crucial role in balancing the fluid pressure within the cochlear chambers. The round window was modeled as a membrane that moves in response to the fluid dynamics inside the cochlea.

Basilar Membrane (BM): The basilar membrane is critical for auditory processing, as it vibrates in response to different frequencies of sound. The membrane was modeled as a flexible structure that varies in width and thickness from the base to the apex. The variation in stiffness along the BM is crucial for modeling its frequency-specific response.

The geometry of these parts was designed in SolidWorks with a clear focus on the dimensions, which were based on existing anatomical data of the cochlea.The dimensions were scaled for simulation purposes.

2. Dimensioning of Cochlea Components

The geometrical features and dimensions of the cochlea were carefully chosen to match those observed in human anatomy. Several studies on cochlear anatomy provided valuable insights into the scaling and dimensions of each component of the cochlea.

3. Material Selection and Properties

For accurate representation, the materials used in the model needed to reflect the mechanical properties of the cochlea's components. The primary components in the model were the basilar membrane and the cochlear fluid.

Basilar Membrane (BM): The BM is composed of a complex biological material that exhibits variable stiffness along its length. This stiffness is critical for its frequency-tuning properties, and it is typically much stiffer at the base and more flexible at the apex. The material properties of the BM were modeled based on experimental data for Young's Modulus, Poisson's ratio, and thickness variations.

Cochlear Fluid: The cochlear fluid was assumed to have properties similar to water, as its behavior is primarily driven by fluid dynamics (density and viscosity), with minimal variation across the cochlea'

Table 5.1-Material Properties

Component	Material Type	Young's Modulus (MPa)	Poisson's Ratio	Density (kg/m^3)	Thickness/Width
Basilar Membrane	Biological Tissue	100 MPa (base) to 2.5 MPa (apex)	0.3–0.5	1100	0.15 mm (base) to 0.5 mm (apex)
Cochlear Fluid	Water-like Fluid	-	-	1000	N/A

The Young's Modulus of the basilar membrane decreases linearly from 100 MPa at the base to 2.5 MPa at the apex.For simplification, the Poisson's ratio for the BM was assumed to be between 0.3 and 0.5 based on typical soft biological tissues.

4. Geometrical Scaling and Validation

To ensure the model's fidelity to real cochlear anatomy, the dimensions of the cochlea were scaled and validated against published data. The cochlea's spiral shape was approximated in the model, and the components such as the BM were carefully positioned to simulate the real structure. Dimensional accuracy was validated against human cochlear anatomy to ensure that all proportions were realistic.

The scaling followed well-established guidelines found in the references. For instance, the Greenwood model for frequency-position mapping was considered for how the cochlear properties (especially the BM) respond to varying frequencies.

5. **Boundary Conditions and Constraints**

For the 3D model to be physically representative of real-life conditions and to simulate the interaction between the fluid and the BM accurately, certain boundary conditions were applied:

The basilar membrane was fixed at both ends, simulating its attachment to the cochlear bony structures.
The oval window displacement was allowed only in the Z-direction to model the sound-induced vibrations transmitted into the cochlear fluid.
The round window was constrained to move only in the X-direction, simulating fluid release to maintain pressure equilibrium.
The cochlear fluid was set to interact with the basilar membrane, ensuring there was no penetration of fluid into the membrane.
These boundary conditions were designed to match the expected physical behavior of the cochlea during sound stimulation.

6. Assembly in SolidWorks

The parts were individually modeled in SolidWorks and then assembled. The Oval Window, Round Window, and Basilar Membrane were carefully placed and aligned within the cochlea's shell. The meshing and component alignment ensured that the interaction between the cochlear fluid and the BM could later be simulated with minimal distortion.

7. Model Refinement

After completing the assembly, the model underwent a refinement process. The dimensions were rechecked, and adjustments were made to improve the accuracy of the basilar membrane's thickness and stiffness gradient. The model was cross-checked against Yen & Hua (2005) to ensure the stiffness gradient of the BM was accurate.

CHAPTER-6
RESULT AND DISCUSSION

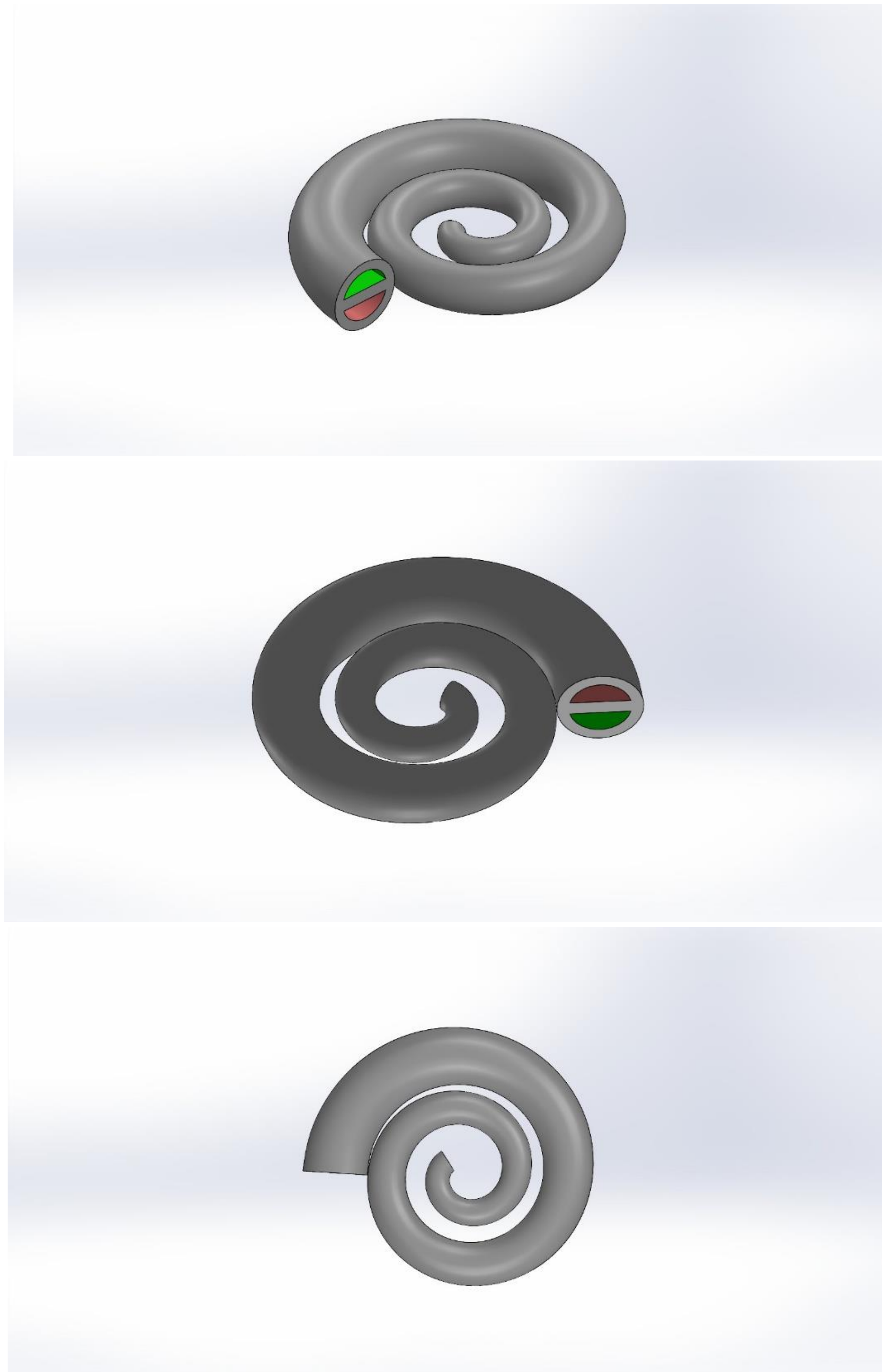

Figure 6.1 : 3D Model of the Cochlea

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Component	Dimension Description	Value
Cochlea Length	Total length of the cochlea	35 mm
Basilar Membrane Length	Length from base to apex	30 mm
Basilar Membrane Width	Width at base (proximal end)	0.1 mm
	Width at apex (distal end)	0.5 mm
Basilar Membrane Thickness	Thickness at base (proximal end)	10 µm
	Thickness at apex (distal end)	5 µm
Cochlea Diameter at Base	Diameter at base of cochlea	4.5 mm
Cochlea Diameter at Apex	Diameter at apex of cochlea	12.50 mm

Table 6.2: Key dimensions used for modeling

While we haven't run simulations yet, building the 3D model has been a valuable first step. It allows us to explore how different interventions might affect the delicate dance of the traveling wave within the cochlea.

1. Electrode Insertion: A Potential Disruption

Imagine a tiny electrode inserted into the cochlea. This foreign object could disrupt the smooth flow of fluids (perilymph and endolymph) inside. Think of it like throwing a pebble in a calm pond – ripples form and distort the original flow pattern. This disruption could cause localized pressure changes and potentially weaken the traveling wave right around the electrode.

Another concern is the electrode making the basilar membrane, the key vibrating structure, a bit stiffer. Imagine a trampoline – a stiff one wouldn't bounce as freely as a loose one. Similarly, a stiffer basilar membrane might not vibrate as easily, potentially affecting how the traveling wave travels and possibly altering its response to different sound frequencies.

Finally, the electrode could act like a speed bump in the cochlear duct, reflecting and scattering the traveling wave. Picture throwing waves at a wall – some bounce back (reflection), while others might bend around the obstacle (scattering). This could decrease the overall wave strength and potentially create more complex wave patterns within the cochlea.

The severity of these disruptions likely depends on where the electrode is placed. Electrodes closer to the cochlear base (responsible for higher frequencies) might have a bigger impact on high-pitched sounds. The size and design of the electrode also matter. Smaller, more flexible electrodes could minimize these disruptions. Future simulations, incorporating the exact dimensions and properties of the electrode, are crucial to understand the disturbances in detail and potentially optimize electrode design for minimal impact.

2. Surgical Opening: A Breach in the System

Imagine creating an opening in the cochlea's wall – a cochleostomy. This disrupts the natural fluid-filled environment, potentially allowing precious perilymph to leak out and affecting the delicate pressure balance within the cochlea. Think of a balloon – a hole lets out air, causing it to deflate. Similarly, a cochleostomy could significantly reduce the overall strength of the traveling wave.

Another concern is the wavefront, the leading edge of the traveling wave, becoming distorted. Imagine a wave approaching a breakwater – the wave gets disrupted and loses its smooth shape. The opening in the cochlear duct acts like a breakwater, potentially causing the traveling wave to lose its coherence.

Finally, the altered geometry due to the opening can change the cochlea's impedance, a measure of how it resists sound vibrations. This can be like changing the gears in a car – the wrong gear makes it harder for the engine to transmit power to the wheels. Similarly, a mismatch in impedance can affect how sound energy is transmitted and how the traveling wave propagates.

The size and location of the cochleostomy significantly impact the extent of these disturbances. Smaller, strategically placed openings might minimize the disruption. Developing surgical techniques that minimize fluid leakage and maintain cochlear integrity are crucial for preserving hearing function. Future simulations can help predict the optimal location and size of cochleostomy based on the desired surgical goals and the potential impact on the traveling wave.

3. Oval Window Puncture: A Delicate Balance

The oval window is like a special portal for sound vibrations entering the cochlea. Puncturing it creates an additional pathway for pressure release, potentially reducing the overall pressure buildup within the cochlea. Think of a pressure cooker – a release valve prevents excessive pressure buildup. Similarly, a punctured oval window might decrease the traveling wave's amplitude.

Another concern is the oval window playing a vital role in impedance matching, ensuring smooth sound energy transmission. Imagine two gears of different sizes trying to mesh – they won't work well together. Puncturing the oval window disrupts this matching, leading to a mismatch in sound energy transmission and affecting the traveling wave.

The size and location of the puncture will influence the severity of these disturbances. Smaller punctures might offer a better balance between gaining access and minimizing disruption. Techniques to repair or reinforce the oval window membrane after surgery could help restore normal pressure balance and cochlear function. Future simulations with different puncture sizes and locations can help assess the impact on the traveling wave and guide surgical approaches.

4. Round Window Puncture: A Different Approach

The round window plays another important role pressure equalization within the cochlea. Puncturing it could limit its ability to release pressure, potentially leading to an increase in the overall pressure within the cochlea and affecting the traveling wave's propagation characteristics.

However, compared to the oval window puncture, a round window puncture might have a lesser impact on the overall fluid flow pattern.
We took different parameters and made a 3D Model of the Cochlea using Solidworks.Here both Cochlea ducts are shown in the figure 1.6.

In further steps we run simulations in order to ensure the Basilar Membrane function in the developed model intact.
We will compare it to the standard models like Greenwood function.
Greenwood [22] formulated a function that relates the frequency of a pure tone to the position of the hair cells, expressed as a fraction of the total length of the Basilar membrane.

$$f = \int_0^x \Delta f = A(10^{ax} - k)$$

where
f is the characteristic frequency of the sound in Hz
A is a scaling constant between the characteristic frequency and the upper frequency limit of the species
α is the slope of the straight-line portion of the frequency-position curve
x is the fractional length from the apical end of the cochlea to the region of interest ($0 < x < 1$).
k represents the deviation from the logarithmic nature of the curve and is determined by the lower audible frequency limit specific to the species

According to Greenwood, for humans, the recommended values for the constants are given by the equation:

$$f = 165.4(10^{2.1x} - 0.88)$$

CHAPTER-7
CONCLUSION AND FUTURE WORK

The development of a detailed 3D model of the human cochlea has provided a solid foundation for our research into the impact of surgical interventions on cochlear function. By visualizing the complex anatomy of the cochlea, we can better understand the potential consequences of surgical procedures.

Key Findings from the 3D Model:

- **Visualizing Cochlear Anatomy:** The 3D model has allowed us to visualize the intricate details of the cochlea, including the spiral-shaped cochlear duct, the basilar membrane, and the organ of Corti.
- **Identifying Critical Structures:** We have been able to identify key structures that are susceptible to damage during surgical interventions, such as the basilar membrane and the delicate hair cells.

Future Directions:

To further our understanding of the cochlea and the impact of surgical interventions, we plan to:

- **Incorporate Biomechanical Modeling:** Develop more sophisticated models that account for the viscoelastic properties of the cochlear tissues and the fluid-structure interactions within the cochlea.
- **Simulate Surgical Interventions:** Conduct simulations to investigate the effects of various surgical procedures, such as cochleostomy, round window puncture, and electrode insertion, on the traveling wave.
- **Analyze the Impact on Hearing Function:** Analyze the impact of these interventions on the cochlea's frequency response, sensitivity, and dynamic range.
- **Explore the Role of Active Processes:** Incorporate the active mechanisms of the outer hair cells into the model to better understand their contribution to sound amplification and frequency tuning.

By combining advanced modeling techniques with experimental data, we aim to develop more effective surgical strategies and improve the outcomes for patients with hearing loss.

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