Effect of position and shape of electrode on resonant frequency of an artificial epithelium membrane for frequency selectivity

Sudha R Karbari1*, Suneel Sankanatti1, Uttara Kumari M1 and Shireesha G2
1Dept of Electronics and Communication Engineering, Rashtreeya Vidhyalaya College of Engineering, Bangalore, India
2Dept of Physics, Rashtreeya Vidhyalaya College of Engineering, Bangalore, India

E-mail: karbari.rsudha@gmail.com

Abstract. Postoperative medical studies by various groups have shown the relevance of electrode position on the hearing outcome of the Cochlear Implant. There are various types of CI in market that are re-evaluated and changed for its functionality. Prior knowledge of the exact position of the electrode within the cochlea is an important parameter of study to improve the electrical stimulation of the hearing nerve for the implants. Similar studies are performed on the artificial epithelium membrane which involves restoring the function of outer and middle ear without bypassing their functionality and providing solution towards a self sustained implantable cochlea. Different shapes of electrodes are evaluated using various structures in dimensional analysis for improving the displacement and the electric stimulation calculated in terms of voltage. Five designs are modelled and optimized for improving the frequency selectivity for its resonance of an epithelium membrane to function as a biomimetic Epithelium membrane. Simulation studies are carried out using FEA analysis tool to introspect and evaluate the tonotopy of the epithelium membrane in terms of electrode shape and position.

Keywords: Nanotechnology, Cochlear Implant, Finite Element Analysis

1. Introduction
In a conventional Cochlear Implant arrangement, the electrodes are simulated through the signal processing part that picks the signals and converts to its digital equivalent. Various designs are deployed and their studies over few investigations reveal that prior understanding and knowledge of the electrode shape and position shows improvement in the perception of hearing of a CI patient. [1-4] It is difficult to fabricate an ideal electrode design for a CI due to many factors that need to be considered for the maximum benefits of a patient. All of the major CI manufacturers have their own electrode design within their manufacturing know how which they after lot of research from the recipients of the implant.[5] A smart electrode design for the CI should aid in protecting the intra cochlear fine structures in the organ of corti.[6] For more than two decades now, MED EL provided patients with variety of electrodes specific to patient requirements with an electrode varying from 27-35mm , the standard intra cochlear multichannel electrode array is a 12 channel device designed to stimulate the spiral ganglion from the basal area to the apex part. The contact separation favors minimum channel interaction in monopolar mode. The fragile soft silicone array preserves the basilar membrane and the organ of corti during the surgery and insertion process. A basilar membrane is a typical plate like structure inside the organ of corti that is solely responsible
for the electroacoustic conversion and sending the appropriate signals to the auditory nerve and hence to the brain for perception of sound.[7] The membrane is sensitive to incoming frequencies and vibrations. Here we propose a flexible polymeric materials that mimics the function of cochlea i.e the epithelium membrane and the process through which the device operates and excites the auditory nerve is through electrodes[8-9]. Here for low cost analysis of the membrane. we have chosen the materials as gold and chromium which is biocompatible in nature.

The placement of the electrode on the membrane has been investigated for its transient response to cochlear implants through various stimulus design but not a detailed analysis with respect to placement of electrodes for various frequencies and checking its response as a frequency analyzer is still under research. The characteristics of electrodes that exist in CI contains Platinum-Iridium wires and composed of silicone carrier with dimensions corresponding to dimensions advanced Bionic Corporation Hi FocusII cochlear implant electrode. To improve the contrast between silicone carrier and surrounding tissues the electrode shaft is sputtered with a very thin layer of gold.

![Figure 1. Three-dimensional model of calcified tissue. made to visualize the electrode position (b). Position of the electrode relative to the basilar membrane [10] The aim of the study is to characterize the optimum position and shape of the electrode on the artificial basilar membrane that is a self sustained cochlea. The design of the basilar membrane as per the literature varies from 28 mm in length and the width varying from 4mm to 1 mm till the basal region.]

2. Epithelium Membrane Design

The process of artificial epithelium membrane development involves the steps to design and model the dimensions of the membrane for the important parameter that is frequencies of the incoming sound waves or vibrations.

2.1 Dimensions

In accordance with the frequency placement theory of greenwood function locations are derived based on the resonant frequency of the incoming sound vibrations characterized by displacement, potential and stress. Six designs are proposed and a relative comparison in terms of the parameters in terms of frequency and the position of the electrode is analyzed.
The design of the epithelium membrane chosen for simulation based on the modelling of parameters. The dimensions of the device are as shown in the figure 2, with the length of 28 mm to a width varying from 4 mm to 1 mm across the length. There are 2 layers for the device fabrication for an electrode array based device with PVDF as structural layer of 25 μm thick and the electrodes are deposited using sputtering of 0.2 μm. The total area of the device in terms of length and width are 28 mm × 4 mm along all the layers of the membrane and the electrodes. The polymer chosen piezoelectric properties of the materials are the key and aid in conversion of vibrations to the actual stimulation that reaches through the tectorial membrane to the auditory nerve and then to the brain for perception of the incoming frequency. The frequencies for stimulation considered after modelling using greenwood function range from 1019 Hz to 3019 Hz with intervals of 100 Hz.

**Table 1.** Modes of vibration and the resonant frequencies of the device

| Modes of Vibration | Resonant Frequency in Hz |
|--------------------|--------------------------|
| 1                  | 1019                     |
| 2                  | 1419                     |
| 3                  | 1819                     |
| 4                  | 2219                     |
| 5                  | 2619                     |
| 6                  | 3019                     |

The stacked layers of the device with PVDF as structural layer and blanket layer of Cr/Au and the top electrode pattern of Cr/Au is as shown in figure 3. The resonant frequencies based on modelling are chosen to be from 1019 Hz to 3019 Hz.

**Figure 3.** The cross sectional view of the materials stack used for the simulation.
The properties of PVDF material for piezoelectric effect are extracted from the literature and can be imported into COMSOL Multiphysics. The values of young’s modulus and the various other parameters are as tabulated below. A wide variety of substrates are chosen for the fabrication and simulation of devices for implant applications. The biocompatibility of the materials chosen with the structural properties is a crucial role. In the study we are proposing 5 new novel designs in terms of its change in position and shape for the electrodes of an artificial epithelium membrane that is capable of replacing the cochlear implants with its self-sustaining properties as the structural material is PVDF.

2.2. Design 1 of AEM

The final closing and the starting position and the location of the electrodes on the ABM are required to be highly accurate in positional dimensions as shown in figure 4.(a)

![Figure 4](image)

*Figure 4.(a). Design 1 of AEM (b). Inset of the electrode distance (c). Displacement plot of Design 1 of ABM*

The inset with the details of the electrode placement shown include minimum gap between the electrodes is realizable. As the structural membrane is piezoelectric in nature, the parameters of study along with the voltage generated are displacement, electric potential, resonant frequency. The values of displacement provides us with the maximum distance that the membrane rises along the Z axis to stimulate the tectorial membrane as the hair cells are not functional in patients with sensorineural applications. PVDF as a structural membrane has two roles to play, to convert the incoming sound waves to electric impulses in correspondence to the frequency of the incoming wave through the concept of place theory of Belesky and the other conversion of the physical motion of the AEM to electrical stimulation bypassing the non-functional hair cells. The shape of the AEM is based on the modelling form the literatures that mimics the naturally existing membrane in the organ of corti. The location of electrodes in the 3 dimensions space including the x, y and z coordinates is tabulated below in table 2. The position and its displacement for the resonant frequencies is tabulated with highest displacement occurring at 0.0028301 mm in the z
space. The number of electrodes onto the membrane ABM are 15 with the spacing between the electrodes changed from 700 μm to 900μm. The displacement plots along the axis of the arc length is defined for a length of 28 mm and the values that are tabulated in table 2.

**Table 2. Displacement and co-ordinates for the design1 of ABM**

| X position | Y position | Z position | Displacement(mm) |
|------------|------------|------------|------------------|
| 4.7237     | 0.41517    | 1.0113     | 0.002767452      |
| 4.7570     | 0.22775    | 1.0348     | 0.002830189      |
| 14.595     | 0.24585    | 1.0131     | 0.001202512      |
| 7.6709     | 0.20842    | 0.63717    | 0.000767324      |
| 4.7327     | 0.27133    | 1.0305     | 0.002818621      |
| 7.6585     | 0.43414    | 0.99714    | 0.002526124      |
| 10.97      | 0.26050    | 1.021      | 0.002113145      |
| 12.158     | 0.31946    | 1.0042     | 0.0008661423     |
| 14.48      | 0.17137    | 1.0258     | 0.001217123      |
| 15.904     | 0.34372    | 0.97434    | 0.000982812      |

ABM for its resonant frequencies ranging from 985.6 Hz to 4024.5 Hz. Each frequency follows a pattern wherein there are harmonics at many locations but there exists one position where there is maximum displacement and the vibration susceptance. The maximum displacement attained using the design 1 is 2.830 μm for the co ordinates of (4.7570, 0.22775, 1.0348). The values are obtained for the first resonant frequency considered at a random sample. The displacement plots from the 3 dimensional plot indicates that the apex region is more susceptible to the vibration with a pressure of 1 Pa at one of its ends in a similar manner as that exists in the natural cochlea. As from the figure 4.4.(c), it is evident that the change is frequency indicates the change in location and henceforth the position onto the membrane. It indicates that the change in frequency or vibration leads to change in place which is resonant to that particular frequency and henceforth the confirmation of Helmholtz place theory for an epithelium membrane. The electric potential or the voltage generated from the device for the electrical output is 0.285 μV.

2.3 Design 2 of the AEM

The design of the electrodes along with shape is changed by 2mm along the x direction. The extrusions are included in the design to provide positional change in frequency.

![Figure 5](image_url)  
*Figure 5.(a). Inset of Design 2 of AEM (b). Displacement plot of Design 2 of AEM.*

A single electrode shape is shown in figure 5.(a) with the minimum spacing of 2 mm from the
successive positions.

Table.3. Displacement and co-ordinates for the design2 of ABM

| X position | Y position | Z position | Displacement(mm) |
|------------|------------|------------|------------------|
| 4.7237     | 0.41517    | 1.0113     | 0.002767452      |
| 4.7570     | 0.22775    | 1.0348     | 0.002820142      |
| 14.595     | 0.24585    | 1.0131     | 0.001202575      |
| 7.6709     | 0.20842    | 0.63717    | 0.000767523      |
| 4.7327     | 0.27133    | 1.0305     | 0.002818623      |
| 7.6585     | 0.43414    | 0.99714    | 0.002526123      |
| 10.97      | 0.26050    | 1.021      | 0.002113189      |
| 12.158     | 0.31946    | 1.0042     | 0.0008661471     |
| 14.48      | 0.17137    | 1.0258     | 0.0028794136     |
| 15.904     | 0.34372    | 0.97434    | 0.0009828125     |

The displacement plots along the axis of the arc length is defined for a length of 28 mm as shown in figure 5 (b). The displacement along the X position, Y and Z are as shown in the table.3 for reference. The maximum displacement occurs at a distance of 4.5 mm from the apex for the first modal frequency. The second harmonics occurs at 14 mm from the apex area and the values corresponds to 2.87 μm in terms of displacement. The values are obtained for the first resonant frequency taken at a random.

2.4. Design 3 of AEM

The design 3 of the Artificial epithelium membrane is as shown in figure. The electrodes of the design 3 are configured in a pair of two to include the effects of the variations in displacement as shown in figure.6. The arrangement of the electrodes in this design reduces the number of channels to provide a precise displacement and introspect the electric potentials.

Figure.6. Design 3 of AEM

The coordinates of the position with respect to the change in displacement is tabulated in Table.4. The maximum displacement occurs with a value of 2.89μm at (7.757, 0.22775, 1.038). The displacement is obtained for the third resonant frequency.

Table.4. Displacement and co-ordinates for the design3 of ABM

| X position | Y position | Z position | Displacement(mm) |
|------------|------------|------------|------------------|
| 4.7237     | 0.41517    | 1.0113     | 0.0027623        |
| 7.757      | 0.22775    | 1.0348     | 0.0028915        |
| 14.595     | 0.24585    | 1.0131     | 0.0012025        |
7.6709 0.20842 0.63717 0.0007672
4.3727 0.27133 1.0305 0.00281236
7.6585 0.43414 0.99714 0.0025261
10.970 0.26059 1.0210 0.0021131
12.158 0.31946 1.0042 0.00086623
14.480 0.17137 1.0258 0.00121722
15.904 0.34372 0.97434 0.00099281
14.503 1.877 0.025028 0.00084629
14.503 1.877 0.025028 0.00084629
26.871 3.631 0.000636 0.00006317

2.5 Design 4 of AEM

The design 4 is an improvisation on the design 3 with the electrodes in both the directions with the pairs along as shown in figure 7. The variation in the placement of electrodes produces a change in the parameters of analysis of our study in depth by varying the shape and position of the electrodes onto the PVDF membrane.

![Design 4 and displacement plot of AEM](image)

Figure 7. Design 4 and displacement plot of AEM

The number of electrodes are reduced as the pairing of two is done. The harmonics are increased as can be observed from the figure 7(c) but the maximum and the first resonant frequency of maximum value provides an electric potential of 0.241 μV. The position and place theory analysis is analyzed and depicted in table 5. The maximum frequency is 2.5261μm for the position at 7 mm from apex. The values are obtained for fifth resonant frequency considered at a random sample.

| X position | Y position | Z position | Displacement(mm) |
|------------|------------|------------|------------------|
| 4.7237     | 0.41517    | 1.0113     | 0.0027642        |
| 4.757      | 0.22775    | 1.0348     | 0.0002847        |
| 14.595     | 0.24585    | 1.031      | 0.0012025        |
| 7.6709     | 0.20842    | 0.63717    | 0.0007672        |
| 4.7327     | 0.27133    | 1.0305     | 0.0028186        |
| 7.6585     | 0.43414    | 0.9974     | 0.0025261        |
| 10.970     | 0.26059    | 1.021      | 0.0021131        |
| 12.158     | 0.31946    | 1.0042     | 0.0008614        |
2.6 Design 5 of AEM

Design 5 of epithelium membrane is as shown in the figure. The details inset of the electrodes for the complete membrane is shown in the figure 8. Here there is a shift in the maximum displacement that occurs for the first resonant frequency.

![Figure 8. Design 5 of AEM](image)

The harmonics are reduced as compared to the previous analysis. Here the shape of electrodes and the size is optimized and the results are shown only for the design with best results.

| X position | Y position | Z position | Displacement (mm) |
|------------|------------|------------|-------------------|
| 4.7237     | 0.41517    | 1.0113     | 0.00276742        |
| 4.7570     | 0.22775    | 1.0348     | 0.00283015        |
| 14.595     | 0.24585    | 1.0131     | 0.00120256        |
| 7.6709     | 0.20842    | 0.63717    | 0.00076701        |
| 4.7327     | 0.27133    | 1.0305     | 0.002818655       |
| 7.6585     | 0.43414    | 0.99714    | 0.002526121       |
| 10.970     | 0.26059    | 1.0210     | 0.002113196       |
| 12.158     | 0.31946    | 1.0042     | 0.00008635        |
| 14.48      | 0.17137    | 1.0258     | 0.001217194       |
| 15.904     | 0.34372    | 0.97434    | 0.0009928         |
| 14.503     | 1.877      | 0.028      | 0.0008467         |
| 26.871     | 3.6310     | 0.00636    | 0.0006312         |

The values of displacement occurs at 15.904 mm from the apex to a maximum value of 9.4214 μm. The values are obtained for the second resonant frequency considered at a random sample. The maximum voltage for this modal frequency.

3. Conclusion

Five unique designs of epithelium membrane are proposed and the device parameters in terms of displacement and voltage are investigated. The optimum design 5 with the high values of displacement and voltage are processed towards the fabrication of masks and the device using PVDF as structural layer.
References

[1] Jeng, Fuh-Cherng & Hu, Jiong & Dickman, Brenda & Lin, Ching-Yu & Lin. 2010 Evaluatio
of two algorithms for detecting human frequency-following responses to voice pitch. Inter
national journal of audiology 50 p14

[2] Friedland DR, Runge-Samuelson C. 2009 Soft cochlear implantation: rationale for the
surgical approach. Trends in Amplification 13 p124

[3] Cohen, Noel L, Roland, J. Thomas Jr, and Fishman, Andrew February 2002 Surgical
Technique For The Nucleus® Contour™ Cochlear Implant Ear and Hearing. American
Auditory Society 23 p59

[4] J.H.M. Frijns, S.L. de Snoo, J.H. ten Kate 1996 Spatial selectivity in a rotationally symmetric
model of the electrically stimulated cochlea. Hearing Research 95 p33

[5] Voie AH, Spelman FA 1995: Three-dimensional reconstruction of the cochlea from two-
dimensional images of optical sections. Comput Med Imaging Graph 19 p377

[6] Khurayzi T, Dhanasingh A, Almuhawas F, Alsanosi A. Shape of the Cochlear Basal Turn
2020: An Indicator for an Optimal Electrode-to-Modiolus Proximity With Precurved
Electrode Type. Ear, Nose & Throat Journal 100 p38

[7] Dietz A, Wennström M, Lehtimäki A, Löppönen H, Valtonen H 2016: Electrode migration
after cochlear implant surgery: more common than expected. Eur Arch Otorhinolaryngol
273 p1411

[8] Donald D. Greenwood 1990 A cochlear frequency-position function for several species-29
years later, The Journal of the Acoustical Society of America. 87 p2592

[9] Postnov, A., Zarowski, A., De Clerck, N., Vanpoucke, F., Officeers, F. E., Van Dyck, D., &
Peeters, S. 2006 High resolution micro-CT scanning as an innovatory tool for evaluation
of the surgical positioning of cochlear implant electrodes. Acta Oto-Laryngologica 126 p467