ELECTRO-QUASISTATIC FIELD SIMULATION OF AN ENDOSTEAL COCHLEA IMPLANT

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Abstract. Cochlea implants can help deaf patients to regain hearing. The implants consist of a microphone, a speech processor and an electrode array implanted in the inner ear in order to directly excite the auditory nerves. Recently, an electrode array has been designed to be implanted without inner ear trauma aiming at combining rest hearing with the electrical stimulation. In order to study the field distribution of this new electrode array, field computations using the Finite Integration Technique have been carried out. The electro-quasistatic approximation has been used.

1 INTRODUCTION

The cochlea is a part of the inner ear. It transforms sound-induced vibrations of the middle-ear into electrical signals in the auditory nerve. In the healthy ear, transduction of sound into electrical impulses is carried through with help of the hair cells. If the hair cells are damaged the actuation of nerve impulses is lost and thus the ability to hear. In this case a cochlear implant can help. The implant consists of an electrode array with many single electrodes. It is introduced into the cochlea following its spiral turns. The electric impulses are generated by a microphone worn behind the patients ear, modified by a speech processor and transmitted across the skin to the electrode array implanted into the inner ear.
There are different concepts for optimizing the "link" between the electrodes and nerve structures. As each insertion means an inner ear trauma, for cases with some residual hearing for high frequencies but profound hearing loss for deep tones a new method was taken into account, in which the electrode does not invade the inner ear fluids but lies in a "crevice" between the spiral ligament and the bony cochlear walls. So far, this development of an "endosteal electrode" is still in a very early stage\textsuperscript{1}.

The stimulation of the acoustic nerve originates from a current flow between the electrodes. Though current spread from a conventional electrode array is quite well-known from a couple of papers, e.g. \textsuperscript{2}, the "endosteal site" for electric stimulation has not been investigated so far. This paper will briefly explain the method implemented for the simulation of the endosteal electrode inside the cochlea. Our problem under study shows a capacitive behaviour and the fields may be regarded as slowly-varying. Therefore, electro-quasistatics (EQS) \textsuperscript{3} gives a reasonable approximation to simulate the fields of the cochlea implants. The time-harmonic EQS equations are discretized by the Finite Integration Technique (FIT). Simulation results for different simplified models of the cochlea are presented here.

2 MEDICAL BACKGROUND

2.1 General information on cochlea implants

The cochlea\textsuperscript{4} transforms sound-induced vibrations of the middle ear into electrical signals in the auditory nerve. The human cochlea is a tube, about 35 mm long, divided longitudinally into three compartments and twisted into a spiral (see Fig. 1 - Fig. 3).

![Figure 1: Cochlea.](image)

The three compartments are: scala vestibuli, scala tympani, and scala media which wind around the spiral preserving their spatial orientation. Reissner's membrane separates
scala vestibuli from scala media, which in turn is separated from scala tympani by the spiral lamina and the basilar membrane. Scala vestibuli and scala tympani are filled with perilymph, a fluid similar to extracellular fluid, while scala media is filled with endolymph, a fluid with a high $K^+$ concentration and a low $Na^+$ concentration.

In the healthy ear, transduction of sound into electrical impulses is carried out by the organ of Corti being located on top of the basilar membrane: waves in the basilar membrane create a shear force on the hair cells, which in turn causes a change in the membrane potential of the hair cell. This is transmitted to nerve cells and from there to the brain. If the hair cells are damaged the actuation of nerve impulses is lost and thus the ability to hear. In this case a cochlear implant can help.

In deaf ears with a total or subtotal loss of hair cells this mechano-acoustic converter does not function any more. In most cases however, the acoustic nerve is still in situ and working which means that it can be stimulated by electric impulses applied in its direct proximity. The idea of the so-called cochlear implant is based on this fact: an electrode array with many single electrodes is introduced into the perilymph fluid of the cochlea following the turns of the cochlear duct from the basal part till the apex. The electric impulses are generated by a microphone worn behind the patients ear, modified by a speech processor and transmitted across the skin to the electrode array implanted into the inner ear. The arrangement of the electrodes allows stimulation of nerve fibers at different levels of the cochlea representing different frequencies in the "acoustic" perception.

The stimulation of the acoustic nerve originates from a current flow between the electrodes. Three main types of stimulation are usual: monopolar, bipolar and common ground. Monopolar stimulation is based on the current flow between one electrode of the electrode carrier and a reference electrode which typically is placed outside the cochlea in the muscle tissue. In bipolar stimulation the current flow takes place between two neighboring electrodes on the carrier. Finally, a current flow between the activated electrode and all other electrodes which were switched to ground is called common ground.
If the current density is high enough signals will activate the acoustic nerve fibres, action potentials will be excited and transmitted to the brain. The number of electrodes on the carrier usually varies between 15 to 24 electrodes. They are placed separately or in pairs on the last 17 to 27 mm of the carrier. The electrodes on the base of the cochlea actuate high frequency tones and electrodes on the top actuate low frequency tones.

There are different concepts for optimizing the "link" between the electrodes and nerve structures. One is to approach the electrodes to the "spindle" of the cochlea, the so-called modiolus, by introducing a pre-curved electrode array - a "contour advance electrode". Another concept is to insert the electrode as deep as possible into the fluid-filled cochlea. In this case the electrode is situated more laterally to the ganglion cells, but may stimulate more cells because of its long course within the cochlea. As each insertion means inner ear trauma, for cases with some residual hearing for high frequencies but profound hearing loss for deep tones a new method was taken into account, in which the electrode does not invade the inner ear fluids but lies in a "crevice" between the spiral ligament and the bony cochlear walls. So far, this development of an "endosteal electrode" is still in a very early stage.

Since the patients’ ears vary individually, the choice of the optimal stimulation rate and pulse intensity often is difficult - especially for patients with bone diseases. In those patients it might happen that not only the acoustic nerve will be activated but also the facial nerve. This is another reason for the need of a good understanding of the electric
fields and the current densities in order to allow for further improvements in cochlear implants.

Figure 4: Sketch of cochlea with locations of conventional (top) vs. endosteal electrode (bottom).

2.2 Conventional Electrodes

In praxi, many different electrode types are used for the implementation in the cochlea. They vary in size, number of electrodes and their placement on the carrier. Here, details of three typical electrode carriers with their electrodes are given: Nucleus 24k consists of 22 ring-shaped platinum electrodes distributed in an area of 17 mm length along the electrode carrier. In the CLARION carrier, 16 hemispherical electrodes were placed in pairs on the carrier, which has a diameter of 0.5 mm. The electrodes’ diameter is 0.3 mm. In the CII Bionic Ear System™, 16 electrodes are placed separately on the carrier. Again, the carrier has a diameter of 0.5 mm.

2.3 Endosteal Electrode

In contrast to conventional electrode arrays, inserted into the perilymphatic fluid of the scala tympani, the endosteal electrode should be placed between two tissue layers. On
the one side is soft tissue (spiral ligament) whereas the opposite side of the probe faces the innermost layer of the bony otic capsule (so-called endosteum).

Figure 5: Cross section of the cochlea with location of endosteal electrode.

Figure 6: Photograph of the tip of the endosteal electrode.

The endosteal electrode array has a total length of 10 mm with 10 electrodes separated by a distance of 0.45 mm and a thickness of 0.3 mm, each. Though current spread from a conventional electrode array is quite well-known from a couple of papers e.g. [4], the "endosteal site" for electric simulation has not been investigated so far.
Figure 7: Location of endosteal electrode in preparation.

Figure 8: Design details of the endosteal electrode.
3 MATHEMATICAL MODEL

3.1 Maxwell’s equations and the EQS model

Maxwell’s equations describe all macroscopic electromagnetic phenomena reflecting the relations between the characteristic quantities of electromagnetic fields, the space- and time-dependent electric and magnetic field strength $E$ and $H$. In applications where the wavelength of the studied electromagnetic fields is large compared to the extension of the studied object the wave propagation phenomena may be neglected, i.e. either electric or magnetic fields can be regarded. These "slowly-varying" fields are denoted as electro- and magneto-quasistatic, respectively.

Electro-quasistatics (EQS) gives a reasonable approximation for slowly-varying fields which can be thought to be free of eddy currents while the effects of the displacement current are dominant. This approximation is valid if the problem under study shows a capacitive behavior, i.e. an electrostatic field, for the idealized model of the static limit with frequency $f \rightarrow 0$. The relation

$$\tau_d = \frac{\mu \sigma d^2}{\varepsilon} \ll \tau_r = \frac{\varepsilon}{\sigma}$$

with the diffusion time $\tau_d$ and the relaxation time $\tau_r$ (units), the permeability $\mu$, electrical conductivity $\sigma$, electrical permittivity $\varepsilon$ and a characteristic dimension $d$ of the system under study can be used as a general criterion for EQS. A derivation of estimations about the regime in which the quasistationary approximation is valid can be found in 7, compare also 8. For the time-harmonic case the criterion

$$|k d| \ll 1 \quad \text{with} \quad k = \omega \sqrt{\mu \varepsilon \left(1 - \frac{i \sigma}{\omega \varepsilon}\right)},$$

where $k$ is the wave number and $\omega$ is the circular frequency $\omega = 2\pi f$ can be used.

According to the EQS assumptions the electric field $E$ is free from eddy currents, so the field can be described uniquely by a scalar potential function (shortly potential):

$$E(r, t) = -\nabla \varphi(r, t).$$

Then, replacing the electric field strength $E$ in Ampère-Maxwell’s law by (3) and after some mathematical manipulations the governing partial differential equation for EQS with time invariant, locally constant material is obtained:

$$\nabla \left[ \frac{1}{\varepsilon} \frac{\partial \varphi(r, t)}{\partial t} + \sigma \varphi(r, t) \right] = \text{div} J_E(r, t),$$

where $\varepsilon$ and $\sigma$ are the permittivity and conductivity tensor, respectively.
3.2 The EQS Simulation Model

There are different approaches for the numerical solution of electromagnetic field problems, e.g. Boundary Element Methods (BEM), Finite Elements Methods (FEM) or Finite Difference Methods (FD). The Finite Integration Technique (FIT) is used throughout this paper. Like FEM, FIT is a volume oriented method, i.e. the whole space in which the solutions shall be computed is covered by small finite volumes like tetrahedron or cuboid. In contrary, BEM is surface oriented, i.e. only the surface of the solution space is discretized. All of these methods have their pros and cons. An important characteristic of FIT is that it consistently transfers Maxwell’s equations into linear operator equations on the grid. Here, consistent means that all vectoranalytical and physical properties of the fields still hold on the grid. Thus, energy conservation and main other properties are ensured for the discrete solutions.

Therefore, for the numerical solution of the differential equation (4) the Finite Integration Technique (FIT) was used. Within FIT discrete linear operators replace the vector-analytical curl-, divergence- and gradient operators. In order to setup the discrete analogue of (4) the discrete divergence operator $\tilde{S}$ and the discrete gradient operator $\mathbf{G} = -\tilde{S}^T$ are needed together with the discrete material operators $\mathbf{M}_\varepsilon$ and $\mathbf{M}_\sigma$ and the vector $\mathbf{\Phi}(t)$ which holds the discrete potential values in the grid points. Then, the discrete FIT equation for the transient computation of the discrete EQS potential $\mathbf{\Phi}(t)$ is given by

$$\tilde{S}^T \mathbf{M}_\varepsilon \tilde{S} \frac{d}{dt} \mathbf{\Phi}(t) + \tilde{S}^T \mathbf{M}_\sigma \tilde{S} \mathbf{\Phi}(t) = \tilde{S} \mathbf{j}(t),$$

(5)

with the discrete current flux vector $\mathbf{j}(t)$. Please note that in general $\mathbf{M}_\varepsilon$ and $\mathbf{M}_\sigma$ are determined by the permittivity $\varepsilon$ and conductivity $\sigma$, i.e. non-linear, time-dependent rank two tensors which are assumed to be piecewise constant functions with $\varepsilon > 0$ and $\sigma \geq 0$ if not stated differently.

3.3 Time-harmonic EQS simulation model

In full analogy to (3) a scalar potential is used to describe the electric field. Yet, as usual for time-harmonic field quantities, the equations are derived for the complex amplitude rather than for the field itself:

$$\mathbf{E}(\mathbf{r}, t) \rightarrow \text{Re}(\mathbf{E}(\mathbf{r})e^{i\omega t})$$

with the complex amplitude $\mathbf{E}(\mathbf{r}) = \mathbf{E}(\mathbf{r})e^{i\phi}$ where $\phi$ is the phase angle of the cosine function.

A derivation in analogy to that of (4) yields

$$\Delta \left[ i\omega \varepsilon \mathbf{\varphi}(\mathbf{r}) + \sigma \mathbf{\varphi}(\mathbf{r}) \right] = \text{div} \mathbf{J}_E(\mathbf{r}).$$

(7)

Hence, a complex Poisson equation, i.e. an elliptic partial differential equation, has to be solved in order to compute the phasor $\mathbf{\varphi}(\mathbf{r})$ of the time-harmonic EQS potential.
Again, FIT is used for the discretization leading to the governing equations

\[
\begin{align*}
(i\omega \tilde{S}M_\sigma \tilde{S}^T + \tilde{S}M_\epsilon \tilde{S}^T) \Phi &= \tilde{S}(M_\sigma + i\omega M_\epsilon) \tilde{S}^T \Phi \\
&= \tilde{S}\tilde{j}.
\end{align*}
\]

The linear system \(\tilde{S}(M_\sigma + i\omega M_\epsilon) \tilde{S}^T \Phi = \tilde{S}\tilde{j}\) has to be solved in order to determine the EQS potential \(\Phi\) with the symmetric material matrices \(M_\sigma\) and \(M_\epsilon\). Obviously, the system matrix is complex symmetric. In the past, extensive numerical studies have been carried out to find most robust and fast solution methods leading to the choice of the Krylov-subspace method BiCGCR with algebraic multigrid (AMG) as preconditioner, see \(\text{12, 13, 14}\) and references therein for more details.

Previous simulations for the conventional electrodes have been carried out using the program package MAFIA 4 which included the EQS model. The more recent program package CST EM Studio\textsuperscript{TM} and CST Studio Suite\textsuperscript{TM} 2006 do not (yet) offer the EQS model. Therefore, we calculated the matrices \(\tilde{S}, \tilde{S}^T, M_\sigma\) and \(M_\epsilon\) within the CST Studio Suite\textsuperscript{TM} 2006 solvers for stationary current problems and electrostatic problems, respectively, and transferred them into MATLAB\textsuperscript{TM} with the M2M tool (supplied by the development team of CST GmbH) in order to set up the EQS system. The system was then solved in MATLAB\textsuperscript{TM} while visualization of the results was carried out again in CST Studio Suite\textsuperscript{TM} 2006.

### 4 Simulation Results

The field simulation is carried out with FIT using the time-harmonic equations according to (8). The geometric model considers the anatomic structures. Many of the simulation models for the cochlea with electrode implant, considering the anatomic structures, model the unrolled cochlea. One of the most elaborated winding 3D models, to our knowledge, has been presented in\textsuperscript{15}, using the boundary element method (BEM).

#### 4.1 Unrolled cochlear model

To gain first results the authors started off with an unrolled non-tapered model, i.e. the cross-section at the entry of the cochlea has been extended 26.2 mm in longitudinal direction (see Fig. 12). Table 1 gives details about the compartment dimensions used in these simulations.

<table>
<thead>
<tr>
<th>Compartment</th>
<th>Length / mm</th>
<th>Cross Section / mm(^2)</th>
<th>Volume / (\mu) l</th>
</tr>
</thead>
<tbody>
<tr>
<td>tympani</td>
<td>26.2</td>
<td>1.22</td>
<td>31.20</td>
</tr>
<tr>
<td>vestibuli</td>
<td>26.2</td>
<td>0.75</td>
<td>19.64</td>
</tr>
<tr>
<td>media</td>
<td>26</td>
<td>0.11</td>
<td>2.76</td>
</tr>
</tbody>
</table>

Table 1: Geometrical data of the three compartments in the unrolled cochlea model.
The unrolled cochlea model is designed in CST Studio Suite™ 2006, considering the Scala Tympani, Scala Media, and Scala Vestibuli, Reissner’s membrane, Basilar membrane and Stria Vascularis. The organ of Corti and the spiral ganglion have been neglected in this model due to their smaller size and their anisotropy. The surrounding space of the model is filled with bone material.

The largest compartment, scala tympani, is separated from the smallest compartment, scala media, by the basilar membrane. On the other side, scala media is separated from scala vestibuli by Reissner’s membrane. For numerical reasons, the thickness of the membranes was enlarged to 0.05 mm. This cochlear model is surrounded by bone as in nature the cochlea has bony walls, too. The material properties of the model are given in table 2.

<table>
<thead>
<tr>
<th>material</th>
<th>conductivity / (1/Ωm)</th>
<th>relative permittivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>bone</td>
<td>0.083</td>
<td>1258</td>
</tr>
<tr>
<td>membrane</td>
<td>1.65·10⁻³</td>
<td>1</td>
</tr>
<tr>
<td>perilymph</td>
<td>2</td>
<td>109</td>
</tr>
<tr>
<td>endolymph</td>
<td>2</td>
<td>109</td>
</tr>
<tr>
<td>electrode carrier</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>electrodes</td>
<td>9.48·10⁶</td>
<td>1</td>
</tr>
<tr>
<td>given potential</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Material data of the three compartments of the cochlear model.

The organ of Corti and the spiral ganglion have been neglected in this first model due to their small size and their anisotropy.

4.1.1 Simulation results for conventional electrodes

First calculations were done with MAFIA 4¹⁶ which is based on the Finite Integration Technique¹¹. Static electric field and the current density were computed by Schulze¹⁷. Figures ?? and 3 show some recent EQS simulations by Schreiber with open boundary conditions.

Figure 9: Current density distribution for the Nucleus 24k model with 22 ring-shaped platinum electrodes. Color plot of absolute value |J| over a length of 1.4 cm.
A preliminary result of the calculations presented by Schulze is the guess that the bipolar stimulation type leads to the smallest scattering of the current density. For a given voltage on the electrodes, the highest chance to generate a nerve impulse is by the common ground stimulation type. Furthermore, for contour advance electrodes it could be observed that the best place for stimulation is inside the scala tympani close to the side of the acoustic nerve.

### 4.1.2 Simulation results for the endosteal electrode

Numerical simulations for comparison of the contour advance electrode with the endosteal electrode with respect to the current spread in modiolus direction and in apical direction, respectively, as well as to side effects in the direction of nervus facialis and the middle ear are foreseen. First simulation results are presented here.

### 4.1.3 Future aspects

These results have to be examined with a more realistic model of cochlea and electrodes. One possibility is to setup a model of 3D data achieved from cuts through a preparation. A CAD model for the bony walls obtained from such preparation cuts with a posteriori added endosteal electrode carrier is shown in Fig. 11. Such CAD model can be read by the program CST Studio Suite \textsuperscript{TM} and then be transferred to an extension of MAFIA 4 which allows for the CFIT extension of the classical Finite Integration Technique\textsuperscript{18} in order to do the time-harmonic EQS simulation. If also anisotropies shall be taken into account the code SAFIT by Motrescu\textsuperscript{19} will be used.
Figure 11: CAD model for the bony cochlear walls obtained from preparation cuts with a posteriori added endosteal electrode (red).

Figure 12: Cross-section of the unrolled cochlear model with a mesh of 1,065,798 grid points. Using CFIT, the boundary approximation is much better than it appears to be from the plot.
Figure 13: Geometry of the unrolled cochlear model.

Figure 14: EQS potential in a cross section at z=21 mm of the mesh with 1,065,798 grid points.
Figure 15: EQS potential in a cross section at y=-0.1 mm of the mesh with 1,065,798 grid points.

Figure 16: EQS potential in a cross section at x=0 mm of the mesh with 1,065,798 grid points.
REFERENCES


[16] CST GmbH, Bad Nauheimer Str. 19, D-64289 Darmstadt, Germany.

