A 3D Model-based Simulation of the Electric Field During Cochlear Stimulation

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Introduction

The goal of research is to acquire an accurate description of the electric field inside an implanted cochlea through validated 3D numerical simulations. The simulation process should accommodate different cochlear geometries and stimulation patterns. Results from this simulation tool will be used to design better personalized cochlear implants with less energy consumptions in the future.

Parametric Cochlear Modeling

Why parametric?

- **Easier and faster 3D reconstruction** from biomedical images, with the potential of achieving automatic reconstruction.
- Guarantees a **derivable mesh surface**. This criterion is required to adopt Symmetric BEM (implemented in OpenMEEG[1]) as the simulation algorithm, which has better accuracy than FEM and other BEMs.
  Enables the **sensitivity analysis** in cochlear geometry, electrode positioning and conductivity changes, through the fine tuning of the parameters.

What is the parametric model?

- **Parametric equations**
  A set of equations describing the central line of the scala tympani / scala vestibuli in a cylindrical coordinate system[2]:

$$R = \begin{cases} C(1 - D\ln(\theta - \theta_0)), & \theta_1 \leqslant \theta \leqslant 100^\circ \\ Ae^{-B\theta}, & 100^\circ < \theta \leqslant \theta_f \end{cases}$$

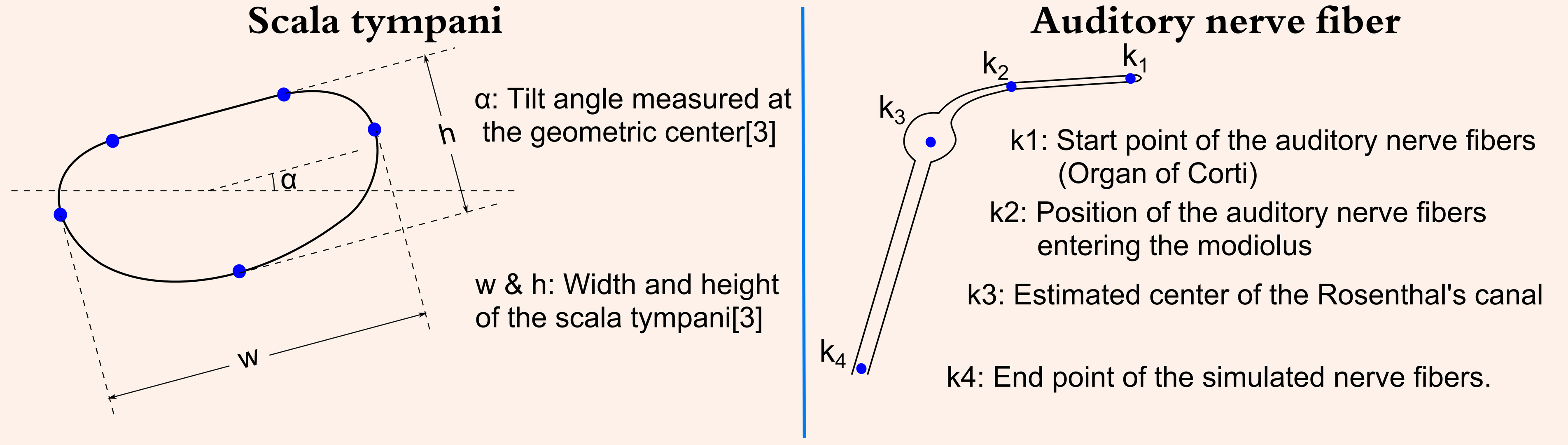
$$z = E(\theta - \theta_1)$$

Parameter values:

A	B	C	D	E	θ_0	θ_1	θ_f
3.762	0.001317	7.967	0.1287	0.003056	5.0	10.3	910.3

- **Coordinates of key points**
  The cross-sections at different positions of the cochlea are determined by key points, which can be acquired through manual measurment or image processing.

Key Points and Cross-Sections



Electrode Array Description

The electrode array description includes the length and diameter of the array itself, and the layout and shape of its electrodes.

In the following sections, the electrode array used for simulation is the EVO electrode array produced by Oticon Medical - Neurelec, which is a straight array with 25mm length and 20 cylindrical electrodes.

EVO electrode array

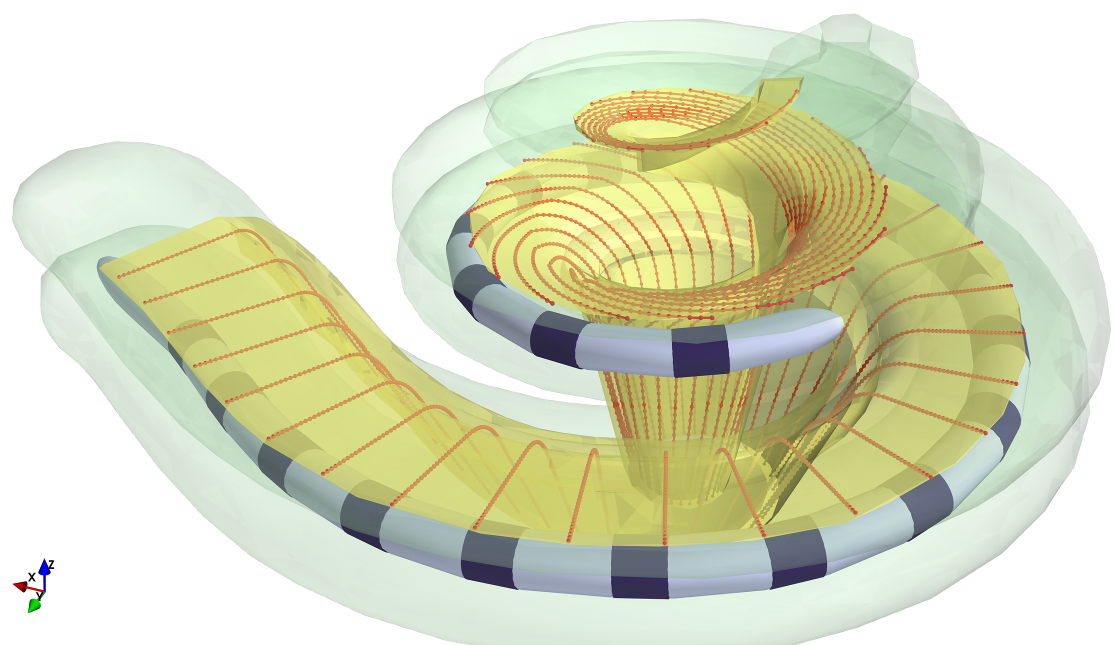
Results: 3D Cochlear Model

The following images show a 3D cochlear model created with the parameters given before. Different parts in the model are marked out by colors: scala tympani and scala vestibuli (light green), electrode array (light blue), metal electrodes (dark blue) and the nerve tissue (yellow).

The total number of the simulated auditory nerve fibers is 200. To have a clearer view of their trajectories, 1/4 of them are visualized as red lines. Each dot on the line represents a simulated measure point of the electric potential.

The input for a electric field simulation is a vector of the current intensities on each electrode of the implanted array. The outputs are the electric potentials at the position of the measure points and on the electrodes.

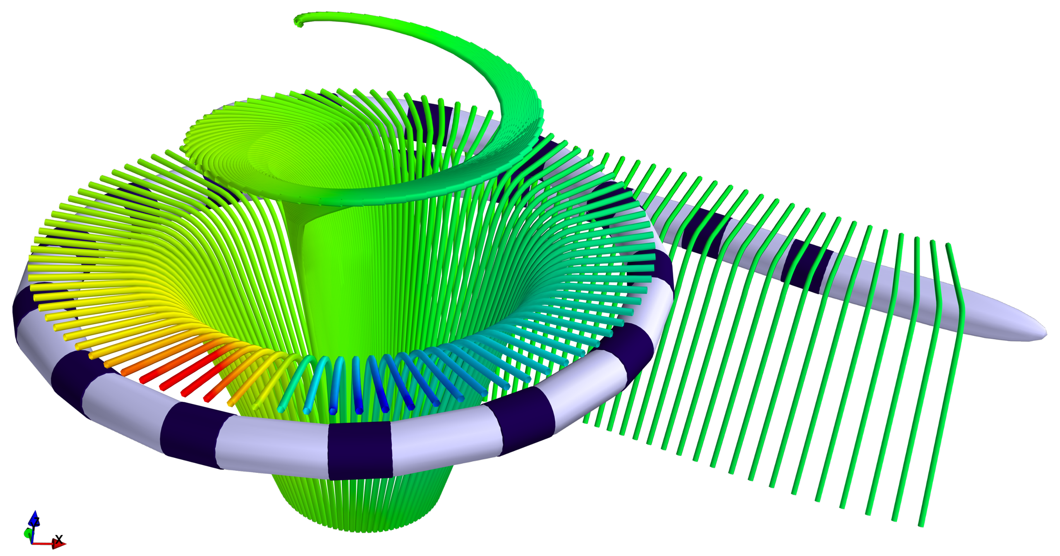
3D cochlear model

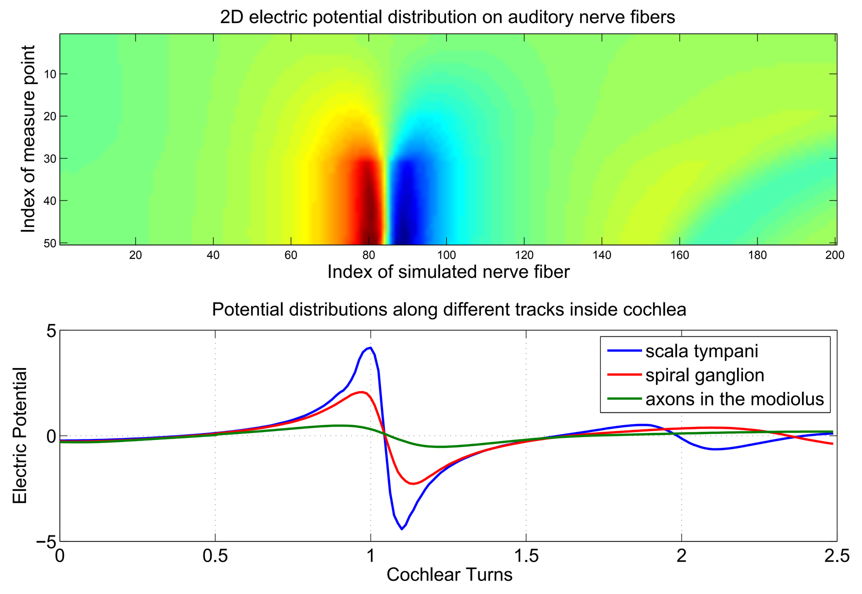


Results: Electric Field Simulation

The electric potential distribution shown in the plots is the simulation result of a bipolar stimulation on the 12th and 13th electrodes of the electrode array. The conducitvity information of the cochlear tissues is from ref [4].

3D electric potential distribution



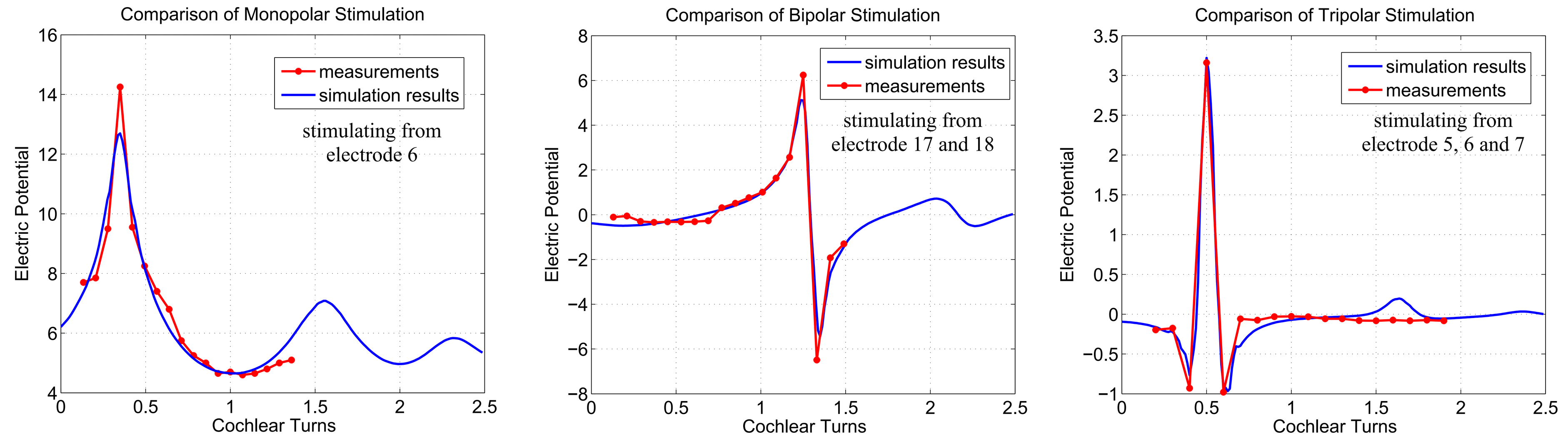


Validation

The validation was made by comparing simulation results with the actual intra cochlear potentials measured from an implanted EVO electrode array in the cochlea of a human specimen.

Stimulation waveforms with typical durations and amplitudes were sent to the electrodes. The potential waveforms on all the 20 electrodes were recorded during each stimulation at 5MHz sampling rate and ±2V, 16bit amplitude quantization. After the measurements, a micro-CT scan was performed on the human specimen to get the positioning of the implanted array. In this experiment, electrode 1 and 2 were found not inserted into the scala tympani.

Results of comparison are shown in the plots. The dots on the red plot represents the potential value measured from the electrodes. The measured potentials are multiplied by a constant to fit the amplitude of simulation results.



The comparisons show a good match between the simulation output and the measurements. This validation experiment is unique because it was performed on a human specimen. Its full analysis will allow to further adapt the 3D cochlear stimulation model to actual patient geometry and physiology.

References

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We will always remember Jonathan Laudanski, who initiated this project, and continue working on the researches he had started.