Modeling potential distributions inside the cochlea caused by electrical stimulation

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During the last decades the average speech intelligibility of cochlear-implant (CI) users has steadily been improved. Nevertheless, problems still occur especially in complex listening situations. One reason for that is the inaccurate signal transmission between CI electrodes and stimulated nerve cells. To develop new methods overcoming this problem, models are required that provide insight into the processes of electrical stimulation inside the complex geometry of the cochlea. This paper presents a detailed model of the electrically stimulated cochlea. The model consists of a virtual three-dimensional representation of the most important structures of the human cochlea. It serves as a basis for the volume conductor model, which was developed using finite element method. It allows for computation of the electrical potentials inside the modeled structures caused by current applied to the CI electrodes. The presented model was used to compare current spread for different electrode positions and configurations. The results show that the model can represent characteristic differences in spatial selectivity and hence be a help in realizing spatially more focused electrical stimulation.

INTRODUCTION

A cochlear implant (CI) is an electronic device to provide a sensation of sound to patients with severe to profound hearing loss. It bypasses damaged parts of the ear by electrical stimulation of the auditory nerve. Due to advances in technology and signal processing, most CI users reach good speech intelligibility in quiet environments. However, complex listening situations remain challenging. One factor contributing to this problem is the electrode-neuron interface. Current applied to the CI electrodes spreads along the fluid-filled cochlea. Therefore, different electrodes can excite overlapping populations of auditory neurons, which leads to channel interactions.

To improve signal transmission between CI electrodes and stimulated nerve cells, deeper knowledge about the processes of electrical stimulation inside the complex

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geometry of the cochlea is required. However, experimental investigations are not practicable due to the small dimensions of the cochlea. Models are a more feasible option. For example, they can be used to investigate the electrical potentials generated by a CI.

In this paper, we present a detailed three-dimensional model of the electrically stimulated human cochlea. The model allows for computation of electrical potentials inside the cochlear structures caused by current applied to CI electrodes. We use this model to compare simulated potential distributions for various electrode positions and configurations.

METHODS

3-D model of the human cochlea

In order to create a model of the electrically stimulated cochlea, a representation of the cochlear geometry is necessary. For this purpose, a 3-D model incorporating all important structures of the human cochlea was developed. To obtain a realistic and detailed representation, histological sections of the human temporal bone served as a basis for modeling.

To create the model, the contours of all important anatomical structures were defined in various cross sections through the cochlear turns. Then the defined contours in the different cutting planes were connected to each other to create solids. Figure 1 shows one of the defined cross sections. Structures that were not modeled were considered to be too small to influence the calculated electrical potentials significantly.

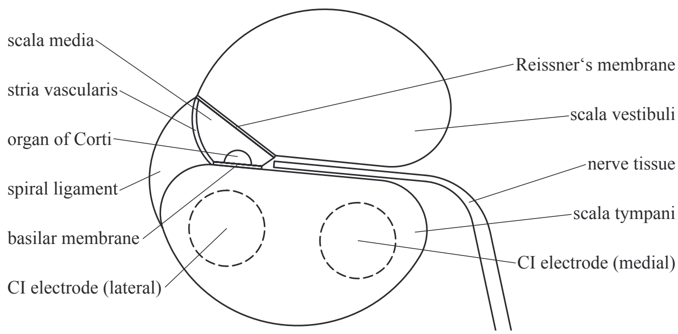

Fig. 1: Cross section through the second cochlear turn containing all modeled anatomical structures of the cochlea and the nerve tissue. The two circles indicate the electrode positions that were modeled: a lateral placement near the outer wall and a medial placement near the modiolus.

The resulting virtual model, which is shown in Fig. 2, was completely embedded into a cylinder with a diameter of 20 mm and a height of 11 mm. This cylinder models bone tissue. In this way, it could be ensured that all gaps were filled.

Fig. 2: Illustration of the created 3-D model of the human cochlea in top view (left) and side view (right). The surrounding bone tissue has been removed for better visualization. The following structures are visible: spiral ligament, nerve tissue, scala vestibuli, and scala tympani.

In addition to the anatomical structures, the implanted CI electrodes were included into the model. Shape and size of the electrodes comply approximately with the Cochlear™ Nucleus® full-band straight electrode. Therefore, 22 banded electrode contacts on a cylindrical electrode carrier were constructed. For the sake of convenience, tapering of the electrode carrier was disregarded. The electrode contacts have a diameter of 0.5 mm and are evenly spaced over a length of 17 mm. The resulting electrode distance is 0.75 mm. The diameter of the electrode carrier is 0.55 mm. Furthermore, the modeled electrode array was placed in two different positions. As shown in Fig. 3, a medial placement close to the modiolus and a lateral placement near the outer wall of the cochlea were modeled.

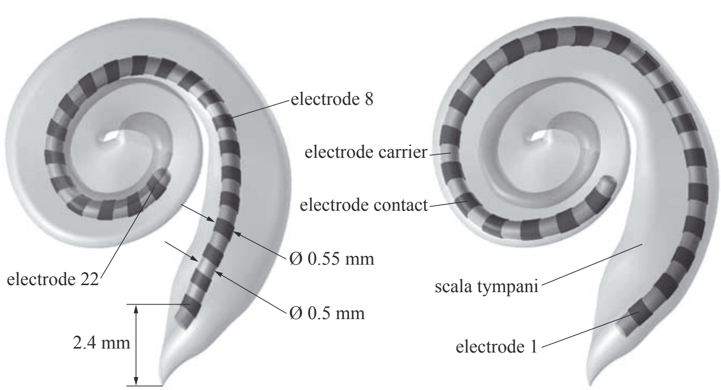

Fig. 3: Visualization of medial (left) and lateral (right) electrode placements inside the scala tympani.

Calculation of electrical potentials

Based on the 3-D model of the human cochlea, a volume conductor model was developed. It was used to calculate the electrical potential distribution inside the cochlear structures as a result of electrical stimulation. Current applied to a CI electrode spreads through the cochlear tissues, which are volume conductors. Hence, a volume conduction problem has to be solved to determine resulting electrical potentials. Because of the electrical properties of the cochlear tissues, the volume conduction problem can be approximated as a quasi-static problem, which is described by Poisson's equation:

$$\nabla^2 \varphi = -\frac{I_s}{\sigma} \qquad \text{(Eq. 1)}$$

where φ is the electrical potential, I_s is the volume current source, and σ is the electrical conductivity. Due to the complex geometry of the cochlea, numerical methods are necessary to solve Eq. 1. For this purpose, the finite element method (FEM) was used.

The FEM model was created using COMSOL Multiphysics®. At first, the created 3-D geometry was imported into the software. Afterwards, the electrical conductivity σ was defined for all modeled structures. All materials were approximated by pure resistances and the values were based on data published by various authors, who developed similar volume conductor models of the cochlea. Table 1 summarizes the values we used in the FEM model.

modeled structure	σ in $\frac{\mathrm{S}}{\mathrm{mm}}$	reference
scala tympani	1.43	Finley *et al.* (1990); Frijns *et al.* (1995)
scala vestibuli	1.43	Finley *et al.* (1990); Frijns *et al.* (1995)
scala media	1.67	Finley *et al.* (1990); Frijns *et al.* (1995)
basilar membrane*	0.0625	Frijns *et al.* (1995); Strelioff (1973)
Reissner's membrane*	0.00098	Frijns *et al.* (1995); Strelioff (1973)
organ of Corti	0.012	Frijns *et al.* (1995); Strelioff (1973)
stria vascularis	0.0053	Frijns *et al.* (1995); Strelioff (1973)
spiral ligament	1.67	Frijns *et al.* (1995); Strelioff (1973)
nerve tissue	0.3	Frijns *et al.* (1995)
bone tissue	0.156	Frijns *et al.* (1995); Suesserman (1992)
electrode carrier	10^{-15}	Tognola *et al.* (2007)
electrode contact	10^{6}	Tognola *et al.* (2007)

Table 1: Specific electrical conductivities σ of the modeled structures in the volume conductor model. For structures marked with an asterisk (*) upscaled values are given (see below).

The modeled solids had to be discretized into smaller tetrahedra. In total, the generated mesh consists of approximately one million elements. To prevent problems with meshing, we upscaled the thicknesses of the basilar membrane and Reissner's membrane by factors of 5 and 10, respectively. To compensate for that, conductivity values of these tissues were also upscaled (see Table 1). This method is in line with that used by Frijns *et al.* (1995).

FEM simulations were performed for two different stimulation protocols. For monopolar electrode configuration the current was applied to one electrode contact. The outer boundaries of the bone cylinder served as ground. For bipolar electrode configuration the current was applied to one electrode and the same current with opposite sign was applied to a neighboring electrode.

RESULTS

Effect of electrode position

Using FEM simulation the potential distribution in all modeled structures can be obtained. To investigate the effect of electrode position, electrical potentials were calculated for monopolar stimulation of electrode 8 with a current of 0.852 mA. Figure 4 compares resulting potential distributions for medial and lateral electrode placements. It shows equipotential lines in a mid-modiolar cross section through the active electrode.

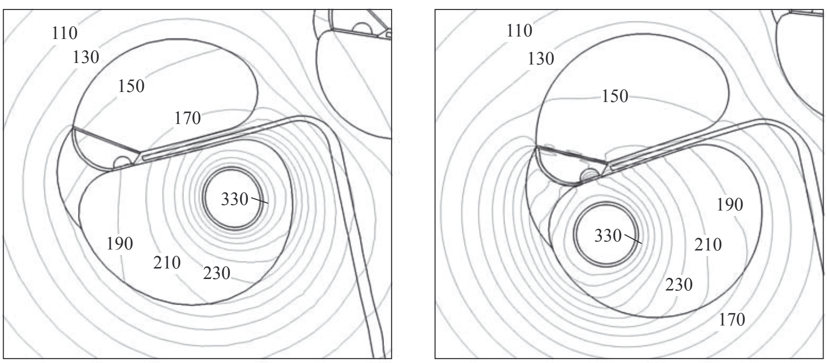

Fig. 4: Equipotential lines in a cross section through the basal cochlear turn for medial (left) and lateral (right) electrode placements caused by monopolar stimulation (0.852 mA) of electrode 8. The numbers indicate the electrical potential in mV. Equipotential lines are spaced by 20 mV. Black lines represent the contours of the modeled cochlear structures.

For the medially placed electrode Fig. 4 reveals higher potential variations in the nerve tissue than for the laterally placed electrode. One reason for that is the smaller electrode to nerve fiber distance for medial placement. Furthermore, current mainly flows along the highly conductive scala tympani. Surrounding tissues like basilar membrane, stria vascularis, organ of Corti, and bone obstruct the current flow, because of their lower electrical conductivities (see Table 1). This is indicated by the accumulation of equipotential lines in these tissues. By contrast, conductivity of the spiral ligament is comparable to that of the scala tympani. Hence, current leaks from the scala tympani through the outer wall, particularly for the lateral electrode placement. As a result, higher current intensities are necessary to excite neurons using laterally placed electrodes.

Effect of electrode configuration

The potential distribution in the nerve tissue is of primary interest because it gives some indication of possible neural excitation. Hence, resulting electrical potentials on the surface of the nerve tissue are shown in Fig. 5 to compare different electrode configurations. It illustrates equipotential lines for monopolar and bipolar stimulation applying a current of 0.852 mA. Electrode 8 served as the active electrode and was placed in medial position.

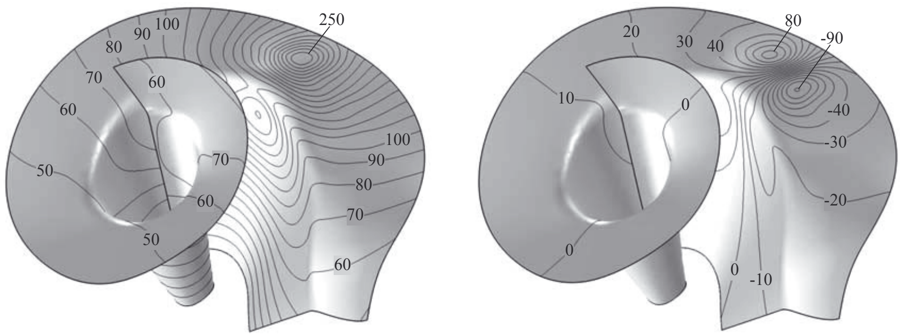

Fig. 5: Equipotential lines on the surface of the nerve tissue for monopolar (left) and bipolar (right) stimulation (0.852 mA) of electrode 8 (medial placement). The numbers indicate the electrical potential in mV. Equipotential lines are spaced by 10 mV.

In Fig. 5 it can be seen that the electrical potential reaches its maximum near the active electrode and falls off with increasing distance. For bipolar electrode configuration an additional potential minimum is visible near the neighboring return electrode and a zero potential line occurs between both electrodes.

By comparison, monopolar stimulation causes a relatively wide spatial distribution of the electrical potential, whereas potential variations are more localized with bipolar stimulation. Furthermore, monopolar configuration induces higher electrical potential values than bipolar configuration. To better illustrate this effect, the electrical potential was calculated along a spiral path on the surface of the nerve tissue near the basilar membrane. The results for all modeled electrode positions and configurations are shown in Fig. 6.

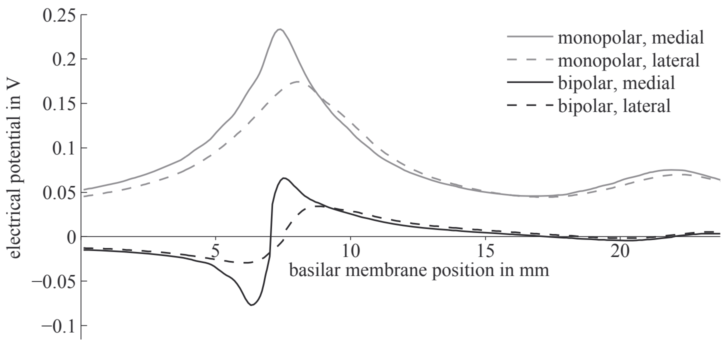

Fig. 6: Course of the electrical potential along a spiral path on the surface of the nerve tissue (close to the basilar membrane) for different electrode configurations and positions. Electrode 8 served as the active electrode.

It is visible that electrode position and configuration influence both spatial distribution and amplitude of the electrical potential in the cochlear tissues. Monopolar stimulation of the medial electrode causes the highest potential values. For laterally placed electrodes the spatial distribution gets wider. Bipolar stimulation produces more localized potentials, but the amplitudes are much smaller in comparison to monopolar stimulation.

Furthermore, Fig. 6 reveals an additional increase of potential values for positions above 20 mm along the spiral path. This position corresponds to nerve fibers one turn above the stimulated electrode. These fibers also have a relatively small distance to the active electrode and may be excited by higher current levels. This effect is called cross-turn or ectopic stimulation and can only be simulated by three-dimensional models of the cochlea.

CONCLUSIONS

In this paper, we have presented a detailed and realistic model of the implanted human cochlea. This model was used to calculate potential distributions inside the cochlear structures. Characteristic differences in spatial selectivity were shown for various electrode configurations and positions. These results are in good agreement with previous findings in the literature, e.g., Briaire and Frijns (2000) and Tognola *et al.* (2007). Hence, the model can be used to investigate different aspects of electrical stimulation.

There are many possible applications of the model. For example, effects of various electrode designs or stimulation protocols on resulting electrical potentials can be evaluated. In this way, the model could be a help in realizing spatially more focused electrical stimulation and consequently reducing channel interactions.

However, in order to infer from the calculated potential distributions about neural excitation, a nerve fiber model is essential. Therefore, further work will concentrate on extensions of the model, to additionally simulate nerve fiber responses. Thus it would be possible to evaluate influences on the spread of neural excitation.

REFERENCES

Briaire, J.J., and Frijns, J.H. (**2000**). "Field patterns in a 3D tapered spiral model of the electrically stimulated cochlea," Hear. Res., **148**, 18-30.

Finley, C.C., Wilson, B.S., and White, M.W. (**1990**). "Models of neural responsiveness to electrical stimulation," in *Cochlear Implants: Models of the Electrically Stimulated Ear*. Edited by J.M. Miller and F.A. Spelman (Springer, New York), ISBN: 9783540970330, pp. 55-96.

Frijns, J.H., de Snoo, S.L., and Schoonhoven, R. (**1995**). "Potential distributions and neural excitation patterns in a rotationally symmetric model of the electrically stimulated cochlea," Hear. Res., **87**, 170-186.

Strelioff, D. (**1973**). "A Computer Simulation of the generation and distribution of cochlear potentials," J. Acoust. Soc. Am., **54**, 620-629.

Suesserman, M. (**1992**). *Noninvasive microelectrode measurement technique for performing quantitative, in vivo measurements of inner ear tissue impedances*, Ph.D. thesis, University of Washington.

Tognola, G., Pesatori, A., Norgia, M., Parazzini, M., Di Luca, R., Ravazzani, P., Burdo, S., Grandori, F., and Svelto, C. (**2007**). "Numerical modeling and experimental measurements of the electric potential generated by cochlear implants in physiological tissues," IEEE Trans. Instrum. Meas., **56**, 187-193.