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Influence of Blood Vessel Conductivity in Cochlear Implant Stimulation Using a Finite Element Head Model

Phillip Tran, *Student Member, IEEE*, Paul Wong, *Student Member, IEEE*, Andrian Sue, *Student Member, IEEE*, Qing Li, and Paul Carter

***Abstract*—It is known that the inclusion of blood vessels in finite element (FE) models can influence the current conduction results. However, there have been no studies exploring the impact of blood vessel conductivity on human head models for cochlear implant (CI) stimulation. The three-dimensional (3D) FE model presented in this paper aims to provide understanding in this regard. The electrical conductivity of blood was varied to determine the sensitivity of the 3D model. The results show that some of the current is exiting the cochlea and taking the jugular vein pathway. When compared to the case with blood vessels being omitted, the current density in the blood increased by 13.1%, 17.2% and 20.7% for low, medium and high electrical conductivity cases considered, respectively. This study suggests that blood vessels cannot be neglected from CI models as the jugular vein can provide a low impedance pathway, through which current can leave the cochlea. It also indicates the importance of using correct tissue property values for performing accurate bioelectric modeling analyses.**

I. Introduction

Cochlear implants (CIs) have helped the hearing impaired community by allowing patients to perceive sound. They work by electrically stimulating the auditory neurons of a patient. The most common arrangement for achieving this is called monopolar stimulation, whereby current is injected into the cochlea via an intracochlear electrode array, and leaves the body at the extracochlear ground electrodes. Ideally, the current would be focused around the target neurons for effective stimulation. However, current may leak and pass through other tissues due to the remote location of the ground electrodes. This leakage can be sizeable enough to prevent proper stimulation of the neurons. As such, more current must therefore be injected in order to reach a minimum stimulation threshold, resulting in higher power consumption. The trade-off between power efficiency and current flow has been noted as an important factor in the design of CIs [1]. It is desired that the current pathways be quantified precisely in order to minimize the amount of power used for stimulation.

One approach for determining the current flow pathways resulting from CI stimulation is the use of finite element (FE) models. While it is known that the internal auditory canal, or the modiolus, is the main current conduction pathway, previous studies have indicated that current can also leave the cochlea via the round window, the facial nerve, and even the surrounding cochlear bone (e.g. patients suffering from otosclerosis) [2]–[5]. In recent studies, it has been suggested that blood vessels, such as the jugular vein, may also play a major role in directing current away from the cochlea due to their close proximity to the source of stimulation [3], [6]. Variations in blood conductivity values for human head models simulating electroencephalography (EEG) have been shown to influence the current conduction in the blood regions significantly, as well as in the entire model in general [7]. On the other hand, Haueisen *et al.* have reported that FE models are not sensitive to blood vessels in magnetoencephalography (MEG) and EEG simulations; however, this finding was attributed to the absence of blood vessels near the source of stimulation [8].

This paper aims to provide the preliminary report on the sensitivity of blood vessels in a human head model during stimulation of the cochlea. It describes the steps taken to create the anatomically accurate three-dimensional model from an image dataset, and the procedure for conducting the sensitivity study. With a lack of human head models looking at the sensitivity of blood vessels, it is also hoped that this FE model could provide fundamental insight into creating better models of the head, and how to improve CI stimulation.

II. Methods

A. Model Creation

The human head model was created from anatomical images of the Visible Human Female (U.S. National Library of Medicine, National Institutes of Health) [9], [10]. 765 images of the head were downloaded and cropped to 530 pixels × 645 pixels. The resolution of the dataset was 0.33 mm × 0.33 mm × 0.33 mm.

The segmentation reported here was an extension to the work conducted in one of our previous models of the human head, which consisted of six tissues [3]. Segmentation of the new tissues was performed using both manual and semi-automatic techniques in Photoshop CS6 (Adobe Systems Inc., San Jose, CA, United States) and ScanIP v4.3 (Simpleware Ltd., Exeter, United Kingdom). A total of 12 tissues were defined: grey matter, white matter, cerebellum, brainstem and spinal cord, nerve, cerebrospinal fluid (CSF), bone, sinus, scalp, eye, cochlea (or perilymph), and blood. Platinum electrodes were also added to the segmentation to simulate CI stimulation [11]. The intracochlear electrode was located approximately halfway around the basal turn of the right cochlea. The extracochlear ball and plate return electrodes were located in the right temporalis muscle and in

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All authors are with the School of Aerospace, Mechanical and Mechatronic Engineering, Faculty of Engineering and IT, The University of Sydney, NSW 2006 Australia (phone: +61293515674; fax: +61293517060; e-mail: phillip.tran@sydney.edu.au, qing.li@sydney.edu.au).

P. Carter is also a Technology Cluster Leader with Cochlear Ltd., Macquarie University, NSW 2109 Australia (e-mail: pcarter@cochlear.com).

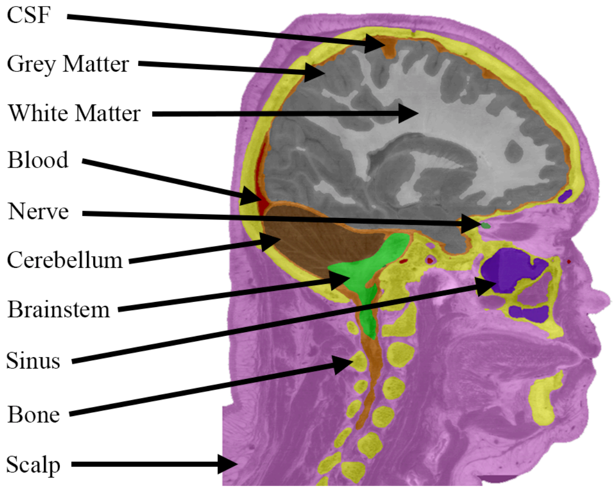

Figure 1. Sagittal slice showing some segmented tissues in the model.

the back portion of the head, respectively. Only one intracochlear electrode was used despite the fact that using multiple intracochlear electrodes would provide a wider range of results. However, it was deemed that doing this was not part of the scope of this study. The segmentation can be seen in Fig. 1.

Surfaces were generated from the segmentation in ScanIP, and were imported as geometries into ICEM CFD 14.0 (Ansys Inc., Canonsburg, PA, United States). The Robust (Octree) mesher was used to create a tetrahedral volume mesh, which consisted of 6,931,888 elements and 1,183,628 degrees of freedom.

B. Simulation

The resultant mesh was saved in Nastran format and imported into COMSOL Multiphysics 4.3a (COMSOL, AB, Stockholm, Sweden). Electrical conductivities were assigned to each tissue as listed in Table 1. All materials were treated as linear isotropic and were based on values obtained from the literature [7], [8], [12]–[20]. The criteria for selecting the conductivity value for a tissue include: (1) the most commonly used value as reported in the literature and (2) an average of a range of values from multiple publications.

Four simulations were performed, each with a different blood conductivity value. The first case simulated CI stimulation without blood vessels present in the model. The second, third and fourth cases included blood vessels with low, medium and high electrical conductivity values, respectively.

For each case, electric boundary conditions were applied to the model to simulate monopolar CI stimulation. A current terminal of 1 mA was applied to the surface of the intracochlear electrode, while the surfaces of the two extracochlear electrodes were grounded.

Simulations were solved with linear discretization using the Direct Pardiso solver in COMSOL Multiphysics. An Intel Core i7 950 computer with 24 GB of RAM was used. Values of current density were obtained from the simulation results using '3D Cut Point' grids in COMSOL Multiphysics. The grids were positioned in the regions of interest to obtain averaged current density values for those regions. The regions studied were the auditory nerve, the scalp tissue located in the region of the middle ear lining, the main region of the jugular vein nearest the cochlea, and the bone tissue surrounding the entire cochlea.

TABLE I. ELECTRICAL CONDUCTIVITY OF MATERIALS

Material	Conductivity (S/m)
Grey Matter	0.33
White Matter	0.14
Cerebellum	0.16
Brainstem and Spinal Cord	0.16
Nerve	0.35
Cerebrospinal Fluid	1.79
Bone	0.0132
Sinus	0.00006
Scalp	0.42
Eye	0.5
Cochlea/Perilymph	1.42
Blood (low/medium/high)	0.568/0.625/0.676
Electrode	9430000

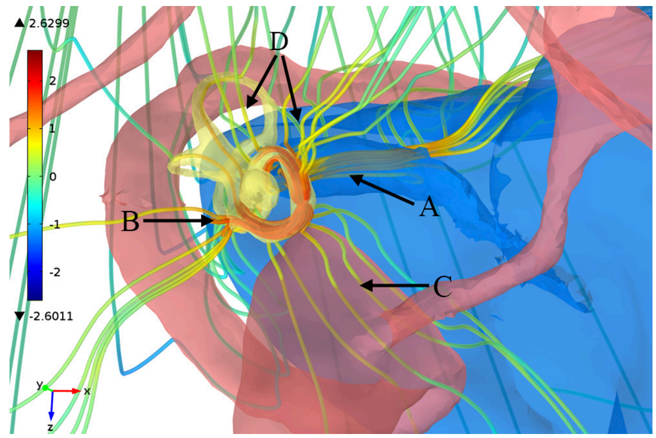

Figure 2. Close up view of the cochlea (yellow volume), nervous tissue (blue volume) and blood vessels (red volume). Major current conduction pathways are shown as current density streamlines: (A) the modiolar pathway; (B) the round window pathway; (C) the jugular vein; and (D) the surrounding cochlear bone.

III. Results

Fig. 2 displays a typical result with 50 current density streamlines originating from the intracochlear electrode, with the cochlea, nervous tissue, and blood vessels included. The streamlines show the paths through which 50 charged particles evenly spaced on the surface of the electrode would travel. The colors of the streamlines show the current density magnitudes in the regions they are passing through on a log scale. They indicate that several pathways, as labeled in Fig. 2, were preferred: (A) the modiolar pathway, with current passing directly to the auditory nerve; (B) the round window pathway, with current passing through to the lining of the middle ear (modeled as scalp tissue); (C) the jugular vein located directly beneath the cochlea; and (D) through the surrounding cochlear bone.

Current density contours of the cochlea, nervous tissue, and blood vessels for the four cases are shown in Fig. 3. The contours represent the current density magnitude (in A/m^2) on the surface of the tissues on an absolute scale. They show that for all four modeling scenarios, the current density

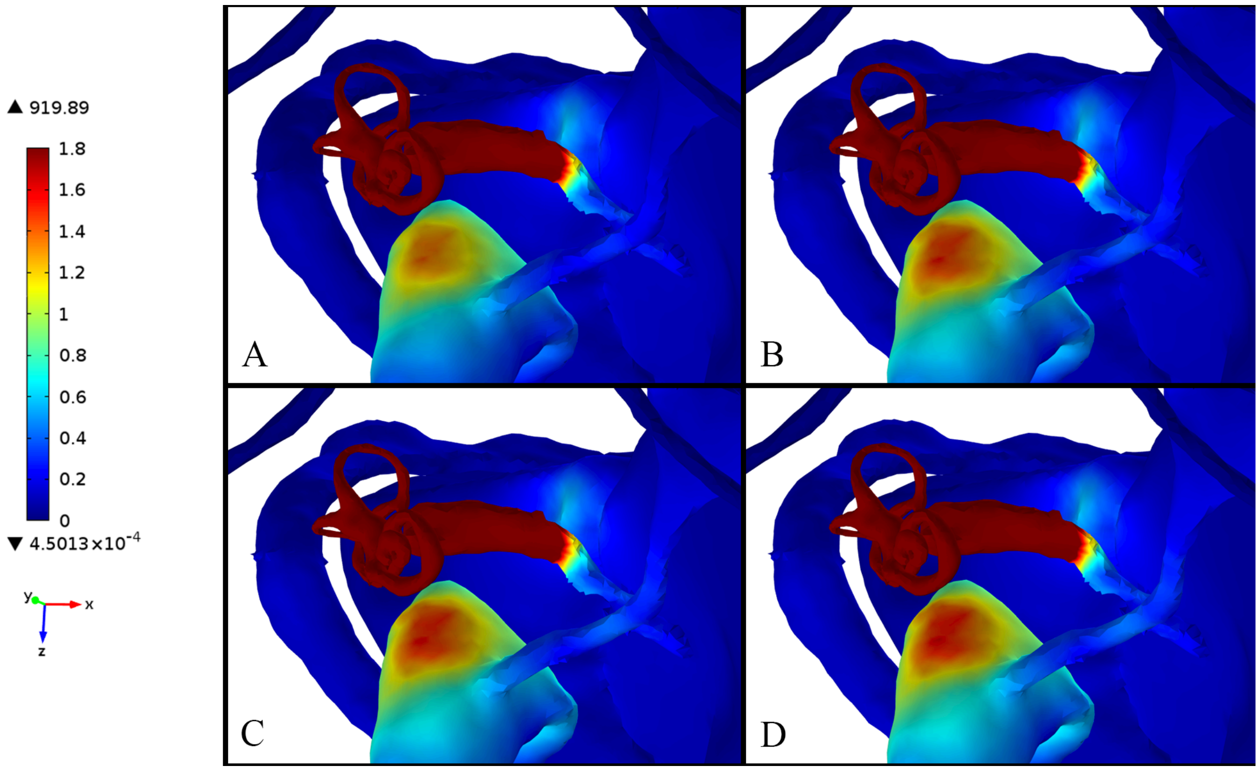

Figure 3. Close up view of the cochlea, nervous tissue and blood vessels showing current density contours under different scenarios: (A) no blood; (B) low blood conductivity; (C) medium blood conductivity; and (D) high blood conductivity.

through the nerve was much higher than that through the blood vessels. Also, there was an increase in the current density through the jugular vein when blood vessels were included in the model (Fig. 3(A) & 3(B)). As the electrical conductivity of the blood was increased (Fig. 3(C) & 3(D)), the current density of the jugular vein increased further. Performing the simulation with low blood conductivity increased the current density of the blood by 13.1% compared with the case with no blood. Similarly, increases of 17.2% and 20.7% were found for medium and high blood conductivity cases, respectively. Nevertheless, the current density in the auditory nerve, the middle ear, and the surrounding cochlear bone did not change significantly (less than 1% decrease) when the blood vessels were included.

IV. Discussion

The modeling indicated that the greatest changes in current density occur in the blood vessels mainly because it was the blood conductivity that was varied in this study. The current densities in the other tissues (nerve, middle ear, bone) did not change significantly. This could be attributed to these tissues being in direct contact with the cochlea, thus making them low impedance pathways from the intracochlear electrode to the ground electrodes regardless of the blood conductivity. It is expected that if the electrical conductivities of the nerve, middle ear, or bone were altered, the current density in all the tissues surrounding the cochlea would be affected. Therefore, it is vitally important to obtain appropriate electrical conductivity values for each tissue, particularly those near the current source and sink, in order to produce an accurate human head model.

Several current conduction pathways were observed from the results. In addition to the modiolar and the round window pathways described previously, the jugular vein played a role as another current conduction pathway to the ground electrodes, supporting the results obtained from our previous study [3]. Even though the current density increased in the jugular vein as the conductivity value of blood was increased, the current density in the other main pathways did not decrease significantly. This indicates that the current is not being redirected away from these current paths, but finding another path to travel through.

It is important to note here that the streamlines shown in Fig. 2 and the contours shown in Fig. 3 are representing current density, and not the current. A larger amount of current passing through a tissue would indicate that the tissue provides a better conduction pathway between the electrodes. On the other hand, a larger current density indicates either a greater amount of current is passing through the tissue, the tissue is smaller in size, or a combination of these. It can be seen that the jugular vein, for example, is larger than the auditory nerve, therefore making the current density much lower, but not necessarily the current. It is hoped that current values are obtained in a future tissue sensitivity study to provide quantitative numbers on the distribution of current from the source of stimulation for CIs.

Only the major blood vessels were considered in this model, namely the jugular veins, carotid arteries, venous sinuses, and vertebral arteries. Other smaller blood vessels were omitted because the existing resolution of the available image dataset made segmentation of these vessels very difficult, if not impossible. In addition, inclusion of such small vessels would increase the complexity of the model and computational cost in creating the model and mesh as well as in performing the simulations. However, it has been shown that small vessels can direct some current away from the cochlea during CI stimulation [6]. These small cochlear arteries and veins are of relatively high electrical conductivity compared to the surrounding tissues making it possible for current to be funneled away from the cochlea through these vessels to the major blood pathways of the head.

In this study, the tissues were modeled as isotropic. However, it is known that biological tissues can display large amounts of anisotropy, such as the white matter and nerves, and these can affect the modeling results in FE analyses [21]. Blood vessel walls can also display anisotropic behaviors due to their layered structure. Thin structures in the body, such as membranes, cell walls and blood vessel walls, may act as an electrical capacitor, whereby charge is stored across the wall [22]. The capacitive effects of these structures can influence the current density distribution for CI stimulation because the stimulation process occurs in a biphasic pulse over time. Therefore, it is highly desirable that capacitive or time-dependent effects are included to further develop the human head model of CI stimulation.

It should be noted that this study only looked at the current pathways for one subject. Changing the size, shape and location of different anatomical features may influence the levels of current flow in the different pathways. As such, it is important to know the variability of geometry in different patients in order to obtain results specific to those patients.

The results offer some insight into how a FE model can be improved, and therefore provide a valuable tool for looking at ways to improve CI design and implementation. One example is the use of current steering techniques, such as changing the location of the extracochlear electrodes, or blocking/limiting the amount of current exiting the cochlea via the round window pathway or through the cochlear bone. Looking at these changes is often difficult in a clinical setting. However, a model such as the one presented in this paper can be used to investigate the effects.

V. Conclusion

This study investigated the influence of blood conductivity on the current pathways during cochlear implant stimulation using an improved FE model of the human head. It was found that the blood conductivity greatly affected the current density through the blood vessels themselves, but not the other tissues surrounding the cochlea. The results highlight the importance of developing accurate FE models using anatomically correct tissue properties, and understanding the sensitivity of the model with respect to these tissues.

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