Three-dimensional reconstruction and finite element modeling for electrical stimulation of human brainstem

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ABSTRACT

Topographical and three-dimensional models of the brainstem segment including the cochlear nuclei were constructed employing computer aided design software. The geometric information was then utilized to construct a finite element model to describe the electric potential distribution in the area for monopolar stimulation. The model demonstrates the effects of ground electrode position on the electric field geometry. Placing the electrode further medial inside the lateral recess increased stimulation of the cochlear nuclear complex.

INTRODUCTION

Finite element methodology was first introduced twenty years ago in structural mechanics. Since then it has been applied to solve problems in many areas where system behavior is described by differential equations. The field of biomechanics has benefitted tremendously from this technique, (Spilker and Simon, 1988). In recent years, finite element techniques have been applied to bioelectric phenomena including direct electrical stimulation of human tissues, (Miller and Henriquez, 1990; Finley et al., 1990; Sepulveda et al., 1983). This paper describes the electric field in the brainstem tissue stimulated by a monopolar central electroauditory prosthesis.

The auditory brainstem implant (ABI) is designed to provide auditory sensations for patients with severed auditory nerves. During acoustic neuroma surgery the cochlea and auditory nerve is removed to gain access to the acoustic tumor mass. A special electrode is inserted into the lateral recess at the time of tumor removal for cochlear nuclear complex (CNC) stimulation. The complex includes the dorsal cochlear nucleus (DCN) and the ventral cochlear nucleus (VCN), which relay the auditory signals to the cerebral cortex. Speech signals are collected by the microphone, processed by the signal processor, and fed into the electrodes through a percutaneous plug or transcutaneous coil. Because of the complexity of the brainstem structures and the inaccessibility of the stimulating area for measurements and evaluation, three dimensional reconstruction of the brainstem and finite element analysis are used to describe the electric fields.
MATERIALS AND METHODS

Two dimensional histologic slides of the human brainstem showing the CNC and surrounding nuclei were prepared by the neuroanatomy lab (Figure 1). The graphic model was then converted into IGES file format and brought into a finite element analysis software AFEMS running in a PC environment (FEM Engineering, Inc.).

![Diagram of brainstem structures](image)

Figure 1. A section of histologic slide. Shaded area is the cochlear nuclear complex.

Projection drawings were made of seven slides which included the cochlear nuclei. The spacing between each histological slide was 0.01476378 inch. The method of reconstruction of a 3D image of the brainstem was summarized in a previous presentation. (Huang, Mobley, and Moore, 1993). The data of the brainstem outline were saved in IGES format. The IGES files were then loaded into the AFEMS's solid modeler. The 3D model was constructed by connecting the brainstem outline of each layer into a surface and extruding it in the Z axis for 0.01476378". The solids were numbered in descending order. 3D meshes were generated on the seven solids in the units of 15 x 10 x 1 along the dorsal-ventral, medial-lateral, and rostral-caudal directions respectively. There were 1050 elements and 2464 nodes in the model. Since the solids had contacting faces, the coincident nodes were combined by the program.
Figure 2. Views of wireframe reconstructed brainstem with auditory structures and the area of lateral recess.

Figure 3. A view of the 3D reconstructed brainstem.
The equations used for the electric-field distribution are detailed in the work by Sepulveda et al., 1983. Tissue conductivity was set at 0.03628 per ohm.cm, based on the paper by Geddes and Baker (1967). The maximum neural stimulating amplitude used by the ABI is not more than 20 microcoulomb/cm²/phase (Eisenberg et al., 1986; McCreery et al., 1990; Shannon, 1992). In the model a DC current source with charge density of either 20 microcoulomb/cm² or 10 microcoulomb/cm² was applied to a group of elements adjacent to the lateral recess. A remote reference was set to zero. Shifting of electrode band position medially was tested in the model. Isopotential contours were drawn to distinguish stimulating areas and signal levels were compared to data in the neural stimulation literature.

RESULTS

A wireframe image of the reconstructed brainstem in four viewing angles is shown in Figure 2 with only the auditory structures displayed. The rectangle represents the area of lateral recess where the surface electrode is placed. Figure 3 shows the reconstructed brainstem with other functional nuclei. Side effects experienced by the patients are related to stimulation of these other nuclei. (Brackmann et al., 1993). For example, stimulation of the cranial nerve VII and IX can cause 'unpleasant facial twitches or tickling sensation at the throat. Stimulation of the spinothalamic and spinal trigeminal tracts (STT) is responsible for pain and temperature sensations. The vestibular structures, including the medial vestibular nucleus (MVN) and lateral vestibular nucleus (LVN) can result in dizziness and nausea when stimulated.

Figure 4a shows the potential distribution when the reference was the far ventral-medial element in Area #1. The active electrode was at the lateral end of the lateral recess (Area #8), and the source charge density was 10 microcoulomb/cm². The reference in Figure 4b is the ventral end element of the third row medial to the midline (Area #1). When overlaying the histologic sections (See Figure 1) with the corresponding extruded solids on which potential contours are plotted, we can tabulate the relation of propagating field and the nuclei location as in Table 1. CNC consistently receives higher signals than other non-auditory nuclei. To examine the level of the stimuli, the charge density is doubled to 20 microcoulomb/cm². The fields take similar shapes as in Figure 4ab, but the potential levels are higher for each area. When the stimulating electrode is shifted medially inside the lateral recess, the field moves accordingly, but the potential levels outside the CNC area are smaller (Figure 4c). This explains why fewer side effect occur in patients when the electrode is placed more medially (Brackmann et al., 1993).
Figure 4. Isopotential contours when the source density is 10 microcoulomb/cm². (a) The stimulation site is laterally located. The ground reference is the most medial-ventral element. (b) Same as a) but the ground is two rows lateral. (c) The stimulation site is more medial than in a) and b), and the ground is same as in b).
Table 1. Potential contour areas where essential nuclei are stimulated.  
(Source charge density and electrode position are the same as in Figure 4b.)

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DISCUSSION

The DCN lies in the floor of the lateral recess and the VCN is covered by the middle cerebellar peduncle. They are invisible to the surgeons and can not be directly accessed. Electrically-evoked auditory brainstem responses (EABRs) indicate the activation of the auditory structures when an electrode is in place. However, the electric field in the tissue being stimulated can not be directly measured. A better understanding of the electric fields produced in the brainstem tissue is needed for improving the auditory stimulation without major side effects. Finite element analysis has proved to be an useful tool in this respect.

There are many factors affecting the electric field in the brainstem, such as changes of stimulation sites, tissue parameters, stimulation modes, ground reference positioning, biphasic signal frequency and amplitude ranges, as well as the variations of the electrode shape and number. These factors work to shift the electric fields present in auditory and other surrounding structures. This model demonstrates the influence of reference electrode positions and signal levels. The more medially the electrode is placed in the lateral recess, the larger the area of CNC stimulated, and the lower the level of signal to other nonauditory nuclei. Further 3D reconstruction and finite element modeling will be used to study different surface implantation sites, the effects of different modes of stimulation, and the electric fields produced by penetrating electrodes.

REFERENCES


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