SOURCE LOCALIZATION USING SPINAL CORD SURFACE POTENTIALS AND MODEL-BASED OPTIMIZATION

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Abstract

Intraspinal microstimulation is being investigated to elicit coordinated motor responses for restoration of function. However, detailed maps of the neuroanatomy of the human spinal cord are lacking. We are developing a method to map motor nuclei in the spinal cord using potentials recorded from the surface of the spinal cord and model-based optimization. A volume conductor model of the spinal cord consisting of two concentric cylinders and an internal monopolar source was developed. Experimental data was simulated by choosing a source location, using the model to generate surface potential data, and adding Gaussian white noise. Constrained optimization was able to identify the source location used to generate the simulated experimental data to within 100μm when noise was = 5%, and to within 250μm when noise was = 10%.

Introduction/Background

Electrical activation of neurons by intraspinal microstimulation is a promising technique to restore function in persons with neurological disorders or injury. One challenge to the clinical application of spinal cord stimulation is determining where to implant the microelectrodes. While organized motor columns have been identified in the human spinal cord [4], detailed maps do not exist, and variation among individuals will have to be accounted for at the time of electrode implantation. Therefore, it is necessary to develop an intraoperative mapping method before intraspinal stimulation techniques can be used clinically. In this study, we are exploring the feasibility of a mapping method based on recording evoked potentials on the surface of the spinal cord.

The long-term project goal is to map antidromically activated motor nuclei of the spinal cord using potential recordings on the dorsal surface of the cord. Inverse problem solutions are generally challenging because multiple solutions exist. However, knowledge of the source [6] can be used to constrain the solution set, and intraspinal potentials produced by motor nuclei upon activation have been characterized [5] [7].

We propose to solve this inverse problem using a forward model in conjunction with an optimization algorithm. The forward model of the spinal cord allows us to prescribe the location of the source and solves for the resulting potentials on the model surface. The optimization algorithm compares the forward model surface potentials with the actual surface potential data and iteratively adjusts the location of the source in the forward model, attempting to minimize the difference between the actual data and the forward model output. When that minimum is found, the location of the source in the forward model is compared to the actual source location to evaluate the degree of success.

This approach was evaluated in simulations using an analytical volume conductor model of the spinal cord. In this paper, the forward model and the optimization algorithm are presented, and the feasibility of the approach is demonstrated by simulation results.

Methods

The forward model is composed of two concentric cylinders of infinite length (Figure 1). The inner cylinder represents the gray matter and has isotropic resistivity, and the outer cylinder represents the white matter and has anisotropic resistivity [3].

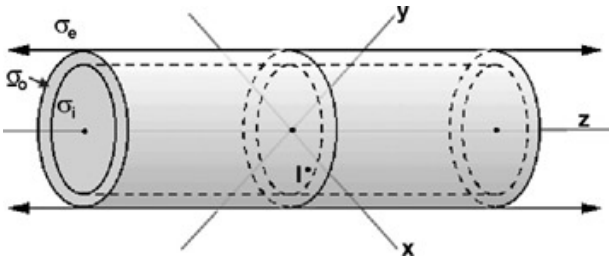

FIGURE 1: The analytic volume conductor model. The conductivities of the gray matter region (σ_i) and the bath (σ_e) are isotropic, while the conductivity of the white matter region ($\underline{\sigma}_o$) is anisotropic. A monopolar current source (I) is located within the gray matter.

The input to the optimization routine was a set of spinal cord surface potential recordings. Surface potentials generated by a single point current source were calculated. Experimental data was simulated by

choosing an arbitrary source location, using the forward model to generate surface potential data, and then adding Gaussian white noise (Figure 2).

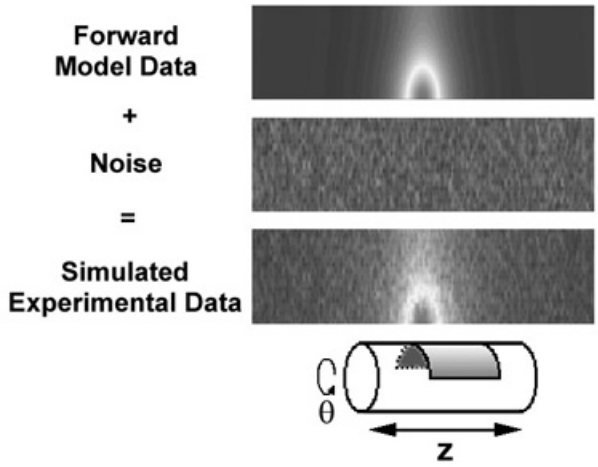

FIGURE 2: Surface potential data generated with the forward model (top) and additive Gaussian white noise (middle) comprised the simulated experimental data (bottom). The cartoon in the lower right illustrates how the potential maps show the voltage on the cylinder surface.

An optimization routine was used to locate the source that generated the simulated experimental data. The objective of the optimizer was to minimize the difference between the simulated experimental data (SD) and the surface potential data generated by the forward model (MD) by iteratively moving the source location in the forward model. The function describing this objective is:

$$e = \left(\Phi_{SD} - \Phi_{MD}\right)^2$$

Prior anatomical knowledge about the source location allowed the optimization search to be constrained. Cells are located in the gray matter of the spinal cord, thus the optimization search was constrained to the gray matter region. Furthermore, the neurons responsible for motor activity are found in the ventral horns of the gray matter, so the search was constrained to the ventral region of the gray matter in some simulations.

The optimization routine searched in one dimension at a time. The z-direction (longitudinal) was searched first, the θ-direction second, and the ρ-direction last. Initial results showed that this 1-D approach gave better results than a 3-D approach.

Results

In the first set of simulations, the optimizer input was a full surface potential data set that covered 4cm along the length of the cord, and the feasible source location was constrained to the gray matter region (Figure 3). In these simulations, the algorithm was able to localize the source to within 2μm under noiseless conditions, to within 30μm with 5% noise, towithin 100μm with 10% noise, and usually to within 200μm with 15% noise (Figure 3). With 15% noise, two simulations resulted in the source location with over 1mm in error, presumably because local minima were created by the noise.

Access to the spinal cord during an intraoperative procedure would likely be limited to the dorsal surface. Therefore, the impact of limiting the circumferential extent of the surface potentials was assessed. In the second set of simulations, the optimizer input was the dorsal half of the surface potential data set, and the feasible source location was constrained to the ventral gray matter region. In these simulations the optimizer was able to localize the source to within 13μm under noiseless conditions, to within 102μm with 5% noise (within 50μm in 9 of 10 cases), to within 212μm with 10% noise (within 150μm in 9 of 10 cases), and to within 140μm with 15% noise (Figure 3).

In the third set of simulations, the optimizer input was the dorsal quarter of the surface potential data set, and the feasible source location was constrained to the ventral gray matter region. In these simulations the optimizer was able to localize the source to within 306μm under noiseless conditions, to within 125μm with 5% noise, to within 230μm with 10% noise (6000^{+} μm in 1 of 10 cases), and to within 520μm with 15% noise (Figure 3).

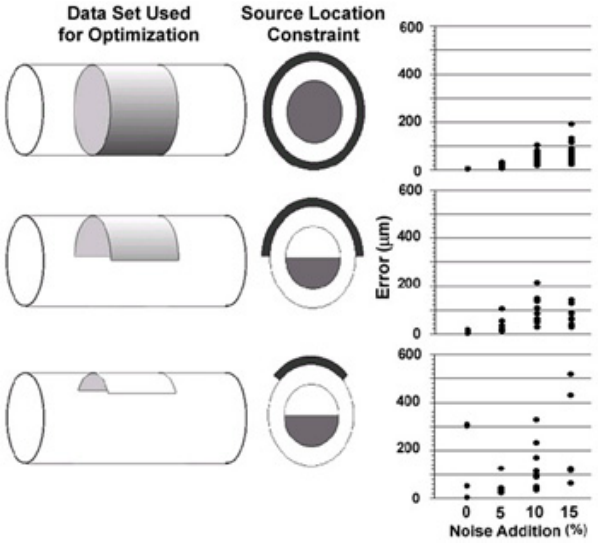

FIGURE 3: Simulation results are shown for cases where either full, half, or quarter data sets were input to the optimizer with varying noise conditions. The optimizer was able to localize the source accurately when noise was = 5%. Localization accuracy decreased when the surface potentials were limited to the dorsal quarter of the spinal cord, or when noise levels increased.

Discussion/Conclusions

We propose to map the location of motor nuclei of the spinal cord using a forward cylindrical volume conductor model of the spinal cord, in conjunction with an optimization algorithm. The optimization algorithm compares the forward model surface potential output with the actual surface potential data and then iteratively adjust the location of the source in the forward model, attempting to minimize the difference between the actual data and the forward model output. This approach was tested using simulated experimental data generated by choosing a source location, using the forward model to generate surface potential data, and adding Gaussian white noise.

The algorithm was generally able to find the source location used to generate the simulated experimental data within 100μm when noise was = 5% , and generally within 250μm when noise was = 10% (Figure 3). We anticipate that the amount of noise in the data set during an experiment can be reduced to low levels (within 5-10%) through signal averaging, giving us the ability to localize to within 100-200μm. Using the quarter data set under noiseless conditions, the optimizer determined the source to be 300+μm away from its actual location in two cases. Analysis of these and other data have led us to reconsider the one-dimensional optimization approach, and a more suitable algorithm is under development.

The results were computed using a single monopolar source. The monopolar source is not meant to accurately represent the motor nucleus that will be stimulated experimentally, but is used because of ease of implementation. Furthermore, any arbitrary source can be produced by super-position of multiple monopolar solutions. Thus, one or more monopoles can be used to model the motor nucleus to the desired degree of complexity.

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