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Identification of material properties from impedances in Spinal Cord Stimulation (SCS) using computational models.

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1. Introduction

Spinal Cord Stimulation (SCS) is an effective therapy to manage refractory chronic pain (Duarte et al., 2020). SCS consists in delivering electrical field targeting the dorsal column fibers of the spinal through a lead array implanted in the epidural space. Thereby, the activation of the dorsal column fibers triggers the inhibitory interneurons as described in the Gate Control theory (Melzack & Wall, 1965).

Computational modelling represents a promising avenue to better understand the target of the electrical field to the dorsal column fibers of the spinal cord. Previous studies rely on a 2-step simulation. First, the electrical field is computed through the Finite Element Method (FEM) at the spine segment scale, with the quasistatic assumption often made. Then, the result of the first simulation was used in a second simulation at the neuron scale to get insight into the electrophysiological behavior of the neural elements of interest (namely, dorsal columns and dorsal root axons, neurons of the dorsal root ganglion and dorsal horn).

A recent systematic review, synthesizing the available models in the literature (Liang et al., 2022), highlighted controversy about some parameters, such as the dura-mater resistivity (Zander et al., 2020). In our study, we investigated the relationship between

impedance measurements (which are routinely obtained in patients with implanted lead array during follow-up visits) and parameters of the finite-element models to validate the simulation.

2. Methods

2.1 Geometry

The spinal canal and spine geometry was based on the PAM50 template (De Leener et al., 2018). The spine was re-segmented to increase precision, The cross section of the spinal cord was based on an anatomical atlas (Kahle et al., 1980).

The iso-surfaces of the segmentations of the spine and Cerebro-Spinal Fluid (CSF) were exported to the stereolithography (STL) format, and then automatically processed using Ansys SpaceClaim. A thickness of 4mm was assigned to the epidural space. Then, a percutaneous lead with 8 contacts (annotated from 0 to 7) was added inside the model. A 0.3mm cylindrical encapsulation tissue, representing the scarring around the lead array, was then manually added around the lead. The geometry was parametrized, using SpaceClaim scripting (fig. 1.a), and allows for some geometrical parameters to be changed to assess their influence. In this work, the thickness of the dura mater was studied.

2.2 Simulation

Ansys MAPDL (Mechanical Ansys Parametric Design Language) was used to solve the Poisson equation. The quasistatic assumption was performed. Dirichlet boundary conditions were added at the lead boundaries of 1 Volts (V) at the nodes between the cathode and encapsulation tissue, and 0 V at the nodes between the anode and encapsulation tissue. An implicitly defined Neumann condition of no outward flowing current was put at the outer boundary of the model. Impedance was calculated through elemental energy. The mesh was refined at the edges of the lead contacts to avoid singularities.

2.3 Design of experiment and response surfaces

Response surfaces are a type of Reduced-Order Model (ROM) consisting in the interpolation of data-points to create a geometrical representation of model output in the parameter hyperspace. To assess the influence of different parameters, a Monte Carlo design of experiment of dura mater, encapsulation tissue and epidural space resistivity as well as dura-mater thickness was drafted using the SALib (Herman & Usher, 2017) python package. Geometries for each dura-mater thickness were automatically generated. For each parameter combination, simulations were run according to different anode-cathode sets. The results were then used to construct a response surface.

3. Results

The influence of the different parameters was assessed using the parametric workflow described above. Response surfaces were computed (fig. 1.b) Average error was estimated to be less than 5Ω (Ohms).

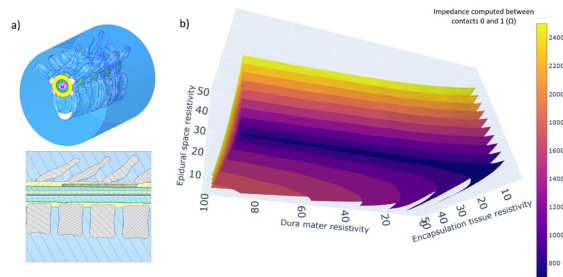


Figure 1. a) One of the generated geometries and a cross-section. b) iso-lines of impedance in the space of the studied resistivities for a dura mater thickness of 0.3mm.

Sobol indices for each parameter were computed (Table 1) using the SALib python package. Those indices revealed that encapsulation tissue resistivity was by far the most important impacting parameter. Surprisingly, dura mater thickness seemed to be the least relevant of those parameters.

Table 1. First order Sobol indices for each parameter for impedance between contact 0 and 1 (eds = epidural space).

Parameter	Sobol index
eds resistivity	0.123
dura resistivity	0.172
encapsulation resistivity	0.605
dura thickness	0.0290

4. Discussion

While some of the impedances computed by the model were found to be within clinical range, these methods still need to be rigorously compared to clinically obtained data. The current approach did not consider lead positioning which is patient specific and has a tremendous impact on measured impedance and clinical outcomes. Patient-specific models should give us more insight into clinically measured impedance data.

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Conflict of Interest Statement

Philippe Rigoard reports grants and personal fees from Medtronic, Abbott and Boston Scientific, outside the submitted work. The remaining co-authors report no conflict of interest.

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