Analysis of Spinal Cord Stimulation and Design of Epidural Electrodes by Computer Modeling

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ABSTRACT
This paper is an overview of the results of computer modeling of spinal cord stimulation, started ten years ago at the University of Twente, The Netherlands. Results are given of the analysis of various geometrical factors, including spinal anatomy, which influence the effect of spinal cord stimulation on nerve fiber recruitment and paresthesia coverage. In a second phase, the computer model was used for the design of new electrode configurations expected to give a better paresthesia coverage in the management of chronic pain. Two new electrode types are presented: the narrow bi-/tripole and the transverse tripole. The latter also enables adjusting the body area affected with paresthesia by means of a dual channel pulse generator giving simultaneous pulses, thereby limiting surgical interventions for electrode repositioning.

KEY WORDS: computer modeling, dorsal column stimulation, epidural electrode, paresthesia coverage, paresthesia steering, spinal cord stimulation

INTRODUCTION
Since the first implantation in 1966 by Shealy et al. (1), neuromodulation of chronic pain by electrical stimulation of parts of the spinal cord (SCS) has evolved to the most common method for the treat-
less pronounced than for an electrode with smaller contact separations. Recently, SCS electrodes with contact separations of 4 mm have become available.

In the past decade, a computer model for the simulation of the primary effects of SCS has been developed and applied to analyze various (geometrical) factors influencing the effects of SCS on the recruitment of dorsal column and dorsal root fibers and paresthesia coverage. Moreover, this model has been applied in the development of different epidural electrodes, which are aimed to enable a wider paresthesia coverage and a better performance in pain management. This paper summarizes the results of these studies.

**METHODS**

A computer model has been developed to calculate the strength (in volts) of a stimulating pulse (applied by an epidural electrode) needed to activate myelinated nerve fibers in the spinal cord. (5–8) These fibers, usually in the dorsal roots and the superficial area of the dorsal columns, are characterized by their positions and calibers. The model consists of two separate parts.

Three-dimensional “volume-conductor” models, made up of $56 \times 56 \times 56$ cubic cells, represent various 60 mm long segments of the spinal cord (white and gray matter) and surrounding anatomical structures (cerebrospinal fluid, dura mater, epidural fat, vertebral bone), which have different electrical conductivities. A transverse section of the low thoracic model is shown in Fig. 1. Epidural electrode contacts are located next to the dura, and their corresponding grid points are set at different voltages (as well as the boundary of the model). Subsequently, the voltages at all other grid points ($\approx 170,000$) of a model are calculated.

The second part of the computer model consists of electrical cable models of myelinated dorsal column and dorsal root fibers with a voltage- and time-dependent nodal membrane resistance, which enables the simulation of an action potential. The voltages in a 3-D model, at positions corresponding to the nodes of Ranvier of a specified fiber, are used to calculate the threshold voltage for its excitation. (6, 7) Constant voltage pulses of 210 $\mu$s duration are generally applied.

Paresthesia in a body segment is caused by the activation of large sensory fibers ($A_\beta$) in the corresponding dorsal column area or dorsal root(let). It is therefore assumed that the paresthesia threshold is identical to the corresponding nerve fiber threshold. Consequently, the computer model can be used to calculate perception thresholds of dermatomal paresthesias and their recruitment order, if the related fiber diameters and positions are known.

Because the computer model, which simulates the primary electrical phenomena related to SCS, is by definition a simplification of reality, its validation is essential. Several validation studies, in which clinical data were used, have shown the predictive capability of the model. (8–11)

**RESULTS**

Causal Relations in SCS

Model calculations predict that currently available SCS electrodes (made up of a rostrocaudal contact array) will, due to their large contact lengths and separations, generally activate dorsal root fibers first. It has also been shown that unipolar stimulation favors dorsal root stimulation most, whereas bipolar
and, even more, tripolar ("guarded cathode") stimulation with neighboring contacts, are most favorable for dorsal column stimulation. (12) The latter model predictions are in accordance with clinical observations: statistically, a narrow bi/tripole gives the widest paresthesia coverage. (3, 4)

Computer simulations also predict that the threshold for dorsal column fiber stimulation gets increasingly higher than the value for dorsal root fibers when the distance between the epidural electrode and the spinal cord gets larger. According to data obtained from transverse magnetic resonance images, (13) this distance is largest at midthoracic levels (T4-T7), resulting in the highest threshold of dorsal column fibers as compared to dorsal root fibers. Clinical experience is in accordance with this model prediction: stimulation at midthoracic levels frequently gives segmental paresthesia (radicular band), resulting from dorsal root stimulation. (11) The electrode-to-spinal cord distance varies strongly both among patients and with the rostrocaudal level of implantation, (13) resulting in a correspondingly large variation of perception threshold (9, 10) and paresthesia coverage among patients.

Clinical studies show that a constant ratio of \( \approx 1.4 \) exists between the maximum and minimum of the therapeutic range-of-stimulation (discomfort threshold and perception threshold of paresthesia, respectively). Because in these patients dorsal root fibers would generally have the lowest threshold, we concluded that both perception threshold and discomfort threshold are related to stimulation of dorsal root fibers (the largest fibers and slightly smaller ones, respectively). (11) Only when the distance between electrode and spinal cord is small (low cervical) will dorsal column fiber thresholds be below dorsal root fiber thresholds. This would result in a ratio of discomfort threshold and perception threshold exceeding 1.4. Indeed, clinical data show a mean ratio of 1.5-1.6 at C5-T1 (Barolat et al., unpublished results).

**Design of SCS Electrodes**

The computer model enables the analysis of the effects of various anode-cathode configurations and positions with respect to the spinal cord on the thresholds of dorsal root and dorsal column fibers, and on the recruitment order of paresthesias, which is related to the recruitment order of nerve fibers in the dorsal columns and dorsal roots. This analysis has been focused on the design of SCS electrodes that promote dorsal column stimulation, while limiting dorsal root stimulation. In this way, the dorsal column area activated within the (increased) therapeutic range-of-stimulation will presumably be increased, as well as paresthesia coverage. Another important aspect taken into account in the electrode design is the limitation of stimulation current and voltage.

**The Narrow Bi/tripole.** The optimal geometry of a rostrocaudal contact array for the preferential stimulation of the dorsal columns has recently been presented. (14) The preferred electrode has contacts of \( \approx 1.5 \) mm rostrocaudally, separated by 2-2.5 mm (edge-to-edge) for both percutaneous and laminotomy electrodes, as shown in Fig. 2.b and 2.d, respectively. The percutaneous one has a similar geometry as a deep brain stimulation electrode (DBS® 3387, Medtronic, Minneapolis, MN). The contact width should be \( \approx 4 \) mm for laminotomy electrodes. Although a smaller contact separation will promote the preferential stimulation of the dorsal columns even more, it will also strongly increase the stimulation current and voltage needed. For comparison, currently available SCS electrodes are shown in Fig. 2.a and 2.c.

**The transverse tripolar lead** (TTL, U.S. Patent No. 5501 703). This epidural electrode is based on the principle that a nerve fiber close to a cathode is depolarized and eventually excited, whereas a nerve fiber near an anode is hyperpolarized. There-

![Figure 2](image-url)
fore, a transverse tripole with a central cathode, flanked by two lateral anodes, has been proposed. (15) See Fig. 2.e. The cathode should have a small rostrocaudal size (1.5–2 mm), which results in an extra reduction of the stimulation threshold of dorsal column fibers, as compared to dorsal root fibers (cf., the narrow bi-/tripole). To further increase this difference, the lateral anodes should be longer. The contacts should be separated by 2.5–3 mm. Apart from “shielding” the dorsal roots, the TTL enables steering of the recruited dorsal column area. In this way, an incomplete coverage of the painful area by paresthesia, resulting from an incorrect electrode placement, can be adjusted electrically. To enable “paresthesia steering,” the TTL has to be used in combination with a dual-channel pulse generator, giving simultaneous pulses of variable amplitudes. (15) This new SCS technique will limit the need for electrode repositioning by surgical intervention.

**DISCUSSION AND CONCLUSIONS**

There are two principal physical limitations of the application of currently available SCS electrodes in the management of chronic pain. First, the threshold for dorsal column fiber stimulation generally exceeds the threshold for dorsal root fiber stimulation (due to the distance between epidural electrode and spinal cord). Second, the small therapeutic range-of-stimulation (≈ 1.4 × perception threshold) limits the dorsal column area that can be stimulated and therefore limits paresthesia coverage and therapeutic efficacy.

These drawbacks of current SCS practice can be limited by reducing the space between the epidural electrode and the spinal cord. This can be done by introducing larger electrodes into the dorsal epidural space, thereby pushing the dura mater towards the spinal cord. In this respect, a laminotomy electrode would be preferable to a percutaneous one, although a favorable effect can also be obtained by introducing two or three percutaneous leads in parallel in the dorsal epidural space. (2) However, this effect may not be sufficient to obtain a complete coverage of the painful area by paresthesia, especially when a patients’ vertebral canal is large at the level of implantation.

The approach in our computer modeling studies has been to take advantage of the different positions and orientations of dorsal column fibers and dorsal root fibers. The electrode geometry was modified in such a way that the electrical field favors the stimulation of dorsal column fibers and suppresses the activation of dorsal root fibers. Although this effect is obtained by both the transverse tripole and the narrow bi-/tripole, the latter configuration will provide the best dorsal column fiber selectivity because the main direction of the current corresponds to the orientation of these fibers. However, only the TTL enables electrical steering of paresthesia.

The predicted performance of the TTL system has been evaluated in a clinical study at the University Hospital “Gasthuisberg” in Leuven (Belgium), in collaboration with Medtronic, Inc. (Minneapolis, MN). Results affirm the model predictions (16).

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**REFERENCES**


