ELECTRODE CONTACT CONFIGURATION AND ENERGY CONSUMPTION IN SPINAL CORD STIMULATION

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OBJECTIVE: To test the hypothesis that in spinal cord stimulation, an increase in the number of cathodes increases the energy per pulse, contrary to an increase in the number of anodes, which decreases energy consumption per pulse.

METHODS: Patients with an Itrel III (7425; Medtronic, Inc., Minneapolis, MN) implantable pulse generator and a Pisces-Quad (3487A; Medtronic, Inc.) implantable quadripolar lead were selected for this study. A set of 7 standard contact configurations was used for each patient. Resistor network models mimicking these configurations were constructed. The University of Twente's Spinal Cord Stimulation software was used to simulate the effect of these contact configurations on large spinal nerve fibers. To allow a comparison of the measured and modeled energy per pulse, all values were normalized.

RESULTS: Both the empirical and the modeling results showed an increase in energy consumption with an increasing number of cathodes. Although the patient data with 1 and 2 cathodes did not differ significantly, energy consumption was significantly higher when 3 cathodes were used instead of 1 or 2 cathodes. The average energy consumption was significantly higher when bipolar stimulation was used instead of monopolar cathodal stimulation. An increasing number of anodes caused a decrease in energy consumption.

CONCLUSION: When the paresthesia area can be covered with several configurations, it will be beneficial for the patient to program a configuration with 1 cathode and either no or multiple anodes.

KEY WORDS: Cathode-anode configuration, Clinical study, Computer model, Energy consumption, Resistor network, Spinal cord stimulation

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Spinal cord stimulation (SCS) is a method to relieve chronic, otherwise intractable pain of neuropathic origin. In SCS, a lead with multiple contacts is positioned in the epidural space over the dorsal aspect of the spinal cord, a few segments rostral to the level where the nerve roots innervating the painful area enter the spinal cord. The epidural lead is connected subcutaneously to an implantable pulse generator (IPG). Electrical pulses applied by a configuration of cathodal and anodal contacts cause a tingling sensation, called paresthesia, in the affected part of the body. Ideally, the comfortable paresthesia covers the pain area completely.

When a battery-powered IPG is used, battery lifetime and energy consumption are patient concerns. Depending on the energy needed for pain relief, a nonrechargeable battery-based IPG has to be replaced within 1 to 7 years (12, 13). Although rechargeable IPGs have recently been introduced by manufacturers of SCS equipment, it is still useful to understand the influence of stimulation conditions on energy consumption. According to a United States Food and Drug Administration safety and effectiveness report, rechargeable IPGs do not need to be replaced as frequently as nonrechargeable batteries, but they do have a lim-

ABBREVIATIONS: 3D, 3-dimensional; **CSF**, cerebrospinal fluid; **DR**, dorsal root; **E**, energy; **E_{MT}**, maximum tolerable energy per pulse; **Imp**, impedance; **IPG**, implantable pulse generator; **PR**, pulse rate; **PW**, pulse width; **SCS**, spinal cord stimulation; **UT-SCS**, University of Twente's Spinal Cord Stimulation; **V_{MT}**, maximum tolerable stimulation voltage; **V_{PT}**, perception threshold of paresthesia ited life span, depending on energy use (15). Therefore, energy-efficient programming will still benefit the patient.

For a voltage-controlled IPG, the energy required for clinically useful stimulation of a patient is dependent on the voltage and duration of the pulses necessary to evoke paresthesia in the patient, the pulse rate (PR), and the total impedance (Imp) between the positive and negative poles. Accordingly, these parameters must be determined to calculate and compare the energy consumption of various contact configurations. If a current-controlled IPG is used, the same parameters, but current instead of voltage, need to be determined.

In SCS, the activation of fibers occurs near a cathode (4). Therefore, the threshold current to activate fibers is determined by the current injected at the cathode. The total current of the anodes is not critical and simply has to equal the total cathodal current. When a single cathode is used in combination with 2 or 3 anodes in parallel, the total anodal current will still be the same as the cathodal (threshold) current. When 2 or more anodes are used, the total anodal Imp will be decreased. Accordingly, the threshold voltage and threshold energy will be less. When 2 or more cathodes are connected in parallel, each cathode needs to inject a (threshold) current. Although the Imp will be decreased, the total current will be increased and the threshold voltage will not be decreased substantially, so that the threshold energy is most likely increased.

The hypothesis tested in this study is that, in contrast to an increase in the number of anodes, which decreases energy consumption, an increase in the number of cathodes increases the energy consumption.

In a clinical study, we determined the energy per pulse (E) of different SCS contact configurations in 10 patients with an implanted SCS system. To determine the effect of the cathode-anode configuration on energy consumption, we determined the maximum tolerable stimulation voltage (V_{MT}) and the Imp of different contact configurations with varying numbers of cathodes and anodes. From these data and the pulse width (PW), which was kept constant for individual patients, the maximum tolerable energy per pulse (E_{MT}) was calculated. In addition, we calculated the E_{MT} while using simple networks of resistors representing contact Imp of the SCS lead and by simulating SCS with the University of Twente's Spinal Cord Stimulation (UT-SCS) modeling software (3) and calculating the E_{MT} at the discomfort threshold.

MATERIALS AND METHODS

Materials

To avoid differences in energy consumption caused by different types of SCS leads and IPGs, we included only chronic pain patients with a Pisces-Quad lead (3487A; Medtronic Inc., Minneapolis, MN) and an Itrel III voltage-controlled IPG (7425; Medtronic Inc.). The latter has the option to stimulate in a monopolar fashion when the IPG is programmed as an anode. The Pisces-Quad lead has a rostrocaudal array of 4 contacts at its distal end (Fig. 1). Each contact can be programmed as an anode (+) or cathode (−) or can be disconnected (0).

To program the different contact configurations and acquire information about energy consumption, an N'Vision Programmer (Medtronic Inc.) was used. This program can be used to measure Imp and current. However, after testing the N'Vision Programmer with a resistor of known value, only the Imp measurements turned out to be reliable and, therefore, were used in the analysis.

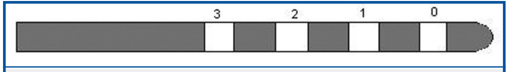

FIGURE 1. *Quadripolar Pisces-Quad lead with 4 contacts (0, 1, 2, 3) at its distal end. The cylindrical contacts have a diameter of ~1.3 mm, are 3 mm long, and are separated by 6 mm.*

Contact Configurations

A set of 7 standard contact configurations, presented in Table 1, was used in each patient. Because of anatomic variability, the different contacts of the lead are most likely at different distances from the spinal cord and will thus cause different threshold values (6, 9). To limit the variation of the output parameters caused by this effect, 1 cathode was kept at the same lead contact in all configurations. The contact configurations were programmed in the same order in all patients.

The 7 standard configurations shown in Table 1 were tested in any patient who used contact 0 or 1 as a cathode in their personal stimulation settings. When a patient used contact 2 or 3 as a cathode, we measured the same configurations as in Table 1, but mirrored them (i.e., configurations 1 and 2 would then be: 0 0-0 and 0 +-+). This was done to avoid unfamiliar and uncomfortable paresthesia in these patients.

Empirical Study and Calculation of Energy Consumption

In each patient, the PW and PR were kept constant in all contact configurations, but the PW and PR could be different among patients. For each contact configuration, the perception threshold of paresthesia (V_{PT}), the V_{MT}, and the Imp were determined. V_{MT}, Imp, and PW were used to calculate the E_{MT} for each configuration, according to Equation 1:

$$E_{MT} = PW * (V_{MT})^2 / Imp \qquad (1)$$

If the injected current at MT (I_{MT}) is known, E_{MT} follows from Equation 2:

$$E_{MT} = PW * (I_{MT})^2 * Imp \qquad (2)$$

TABLE 1. The standard set of contact configurations selected on a Pisces Quad lead and tested in all 10 patients[a]

Configuration	Contact no.			
	0	1	2	3
1	0	−	0	0
2	+	−	+	0
3	0	−	−	0
4	+	−	+	+
5	0	−	+	0
6	−	−	−	+
7	0		+	+

[a] 0, contact is disconnected; −, contact is a cathode; +, contact is an anode.

To allow an accurate measurement of the output parameters, PW and PR were chosen such that the V_{PT} and V_{MT} in each patient were between 2 and 9 V. Patients were seated in a comfortable chair and postural changes of a patient during a test session were limited as much as possible to avoid variations of perception caused by changing positions of the contacts with respect to the spinal cord. To check whether the body area stimulated by a certain contact configuration differed from the normal paresthesia felt by the patient, the area of the paresthesia for each configuration was indicated by the patient and was noted on a body map. To keep the patients focused on the paresthesia area, questions about their perception were asked throughout the tests.

Between measurements, the stimulator was switched off and the next contact configuration was programmed. To determine the V_{PT} and V_{MT} for each new configuration, the stimulation amplitude, starting at 0 V, was increased in increments of 0.1 V until the V_{PT} and V_{MT} were reached.

Resistor Network Models

As a first approximation of the effect of varying the contact configuration on energy, we mimicked the configurations by simple resistor networks. Each cathode and each anode were represented by a 450-Ω resistor and included the wire connected to the IPG output. In monopolar cathodal stimulation, the resistance of the distant anode was 150 Ω.

Although systematic studies on SCS electrode Imp are not yet available, it is well-known from clinical experience that the mean Imp (including lead cable and extension cable) in bipolar and monopolar stimulation is approximately 900 Ω and 600 Ω, respectively. Therefore, a single contact on the lead represents a mean Imp of approximately 450 Ω. Accordingly, in monopolar stimulation, the metal case of the IPG should have an Imp of approximately 150 Ω. These values were applied in the resistor network models.

Cathodes were connected in series with anodes, as shown by cathode Rc and anode Ra in Figure 2A. When a configuration consisted of multiple cathodes and/or anodes, these were respectively connected in parallel, as shown by the anodes Ra1 and Ra2 in Figure 2B. PW was set at 0.2 ms, and the cathodal threshold current for fiber excitation was assumed to be 1 mA. The equations for the equivalent total resistance corresponding to monopolar stimulation and tripolar stimulation are given in the legend to Figure 2, A and B, respectively. According to Equation 2, the E_{MT} was derived from the calculated equivalent Imp, PW, and I_{MT} for all contact configurations (Table 1) and normalized.

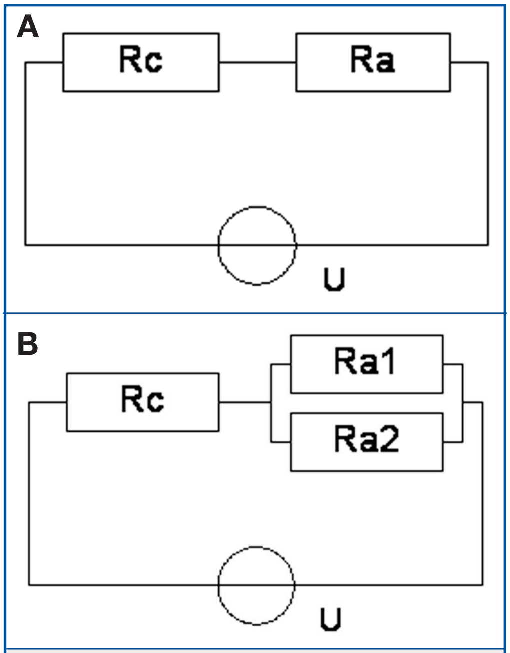

FIGURE 2. *Examples of resistor networks mimicking monopolar stimulation (0-0 0) with resistance of the cathode (Rc) (Rc = 450 Ω, including resistance of the lead wire) and resistance of the distant anode (Ra) (Ra = 150 Ω) connected in series: Imp = Rc + Ra = 600 Ω (**A**) and tripolar stimulation (+-+ 0) with the resistances of the anodes (Ra1 and Ra2) mutually connected in parallel and in series with Rc: Imp = Rc + [(Ra1) · (Ra2)]/[(Ra1) + (Ra2)] = 525 ohm (**B**). U, voltage source.*

Computer Modeling

The UT-SCS software is a simulation program developed at the University of Twente to model the immediate effects of SCS on spinal nerve fibers (3). The software includes 3-dimensional (3D) volume conductor models of spinal cord segments with an epidural SCS lead and represents the geometry and electrical conductivity of the various anatomic structures in a spinal cord segment, such as the gray and white matter of the spinal cord, the surrounding cerebrospinal fluid (CSF), the dura mater, epidural fat, and vertebral bone. The Pisces-Quad lead was modeled symmetrically in the dorsal epidural space, and anodes and cathodes were set at a positive or negative potential, corresponding to each standard configuration (Table 1).

The average geometry of the 3D model was based on magnetic resonance imaging (8), and the electrical conductivities of the various anatomic structures were either taken from the literature or calculated from simulation data (10). Because the average thickness of the low-thoracic dorsal CSF layer is 3 to 4 mm, we used the model with a dorsal CSF layer thickness of 3.2 mm. Data on the real thickness of the CSF layer in individual patients were not available because proper postimplantation computed tomographic scans are seldom performed.

Furthermore, the software includes electric cable models of large-diameter dorsal column and dorsal root (DR) fibers. These fibers are defined at the anatomically correct places in the 3D models, and the field potentials corresponding to their nodes of Ranvier are used as the input of the nerve fiber models. By varying the stimulation voltage between anodes and cathodes, the threshold voltage of the lowest threshold dorsal column fiber and DR fiber were determined. The V_{PT} was reached when the membrane voltage of the fiber with the lowest threshold, either the dorsal column fiber or the DR fiber, was depolarized by 70 mV. The discomfort threshold was defined as 1.4 times the voltage necessary to excite the lowest threshold of the DR fiber (2). In all threshold calculations, PW was 0.21 ms.

Data Processing and Analysis

The paresthesia and discomfort thresholds as used in the modeling are more explicitly defined than the comfort level for a patient, which can be anywhere between these two thresholds. Therefore, we chose to compare the modeled discomfort thresholds with the V_{MT} for the individual patient. In the patients, V_{MT} is presumably just below the discomfort threshold level. To allow a comparison of the measured and the modeled E, they were all normalized in the same way. First, for each patient, the E_{MT} of each contact configuration was normalized to the value of the monopolar configuration (Table 1), which was set at 1.0. Next, the normalized E_{MT} values of all configurations with the same number of cathodes or anodes were averaged for each patient.

These average values per patient were then used to obtain the overall average E for the configurations with 1, 2, or 3 cathodes and with 0, 1, 2, or 3 anodes. In all patients, the 7 standard configurations from Table 1 were acquired.

According to the Shapiro-Wilks test, the patient data are normally distributed. Analysis of variance was performed to identify whether there was a significant effect in E. To determine the significance of the differences in the averaged E between configurations with different numbers of cathodes or anodes, a paired *t* test was performed and the Holm-Bonferroni method was used to correct for multiple testing.

RESULTS

Patients

Patient characteristics are presented in Table 2. Ten patients were included in this study (3 women, 7 men) with an average age of 60 years (standard deviation, 12). All had at least 2 years of experience with SCS and a good or very good effect from the stimulation, resulting in an average pain relief rating of 81% (standard deviation, 9%). The majority received SCS for treatment of chronic diabetic neuropathic pain. One patient had complex regional pain syndrome type I, and 2 patients had failed back surgery syndrome. One patient had the lead positioned over the cervical segments of the spinal cord; all other patients had the lead over the lower thoracic segments. The acquired data for the cervically positioned lead did not differ from the thoracic data.

Effect of the Number of Cathodes/Anodes on Energy Consumption

In Figure 3, the E_{MT} of the various contact configurations is plotted. Figure 3, A and B shows the E_{MT} for contact configurations with an increasing number of cathodes and anodes, respectively. In this figure, the values of all measured configurations with the same number of cathodes (Fig. 3A) and anodes (Fig. 3B) are averaged. It is shown that energy consumption increases with an increasing number of cathodes and decreases with an increasing number of anodes (starting with 1 anode) of the SCS contact configuration. Although quantitatively different, both the empirical and the modeled results (resistive networks and SCS models) show a similar tendency.

From Figure 3A, it is evident that the E values measured in the patients increase less than in both models. Even though the patient data with 1 and 2 cathodes do not differ significantly ($P = 0.4$), E_{MT} is significantly higher when 3 cathodes are used instead of 1 cathode ($P = 0.004$) or 2 cathodes ($P = 0.003$). Figure 3B shows that monopolar stimulation costs least energy. Adding 1 anode increases the energy consumption greatly, while adding 2 or 3 anodes again decreases the E_{MT}. As in Figure 3A, the modeled results in Figure 3B display the effect on E in a better defined way. Nevertheless, the empirical data clearly show the same trend. E_{MT} measured in patients is significantly less ($P = 0.001$) when, instead of 1 anode, the configuration has none (monopolar cathodal stimulation). Using 2 or 3 anodes instead of 1 also results in a significantly lower E_{MT} ($P = 0.04$ and 0.001, respectively). Using 3 instead of 2 anodes causes a significant decrease in E ($P = 0.004$).

Averaging the values for configurations with equal numbers of cathodes and anodes is legitimate because the same pattern is demonstrated in configurations in which the number of anodes is kept constant and only the number of cathodes is increased (Fig. 3C). The same is true for configurations in which the number of cathodes is kept constant and the number of anodes is increased (Fig. 3D).

Among the 7 standard configurations, those with different numbers of cathodes are not equally distributed. Five combinations have 1, one has 2, and one has 3 cathodes. The distribution of configurations with different numbers of anodes is more even because there are two configurations without anodes, two with 1, two with 2, and one with 3 anodes. Despite this limitation, the patient outcomes are normally distributed. Moreover, the empirical trends are in accordance with the trends predicted by the resistor networks and volume conductor models, although the influence of the number of cathodes or anodes on the energy consumption in patients is less distinct. The variations among the individual patients are relatively small, and the E_{MT} is better predicted by the SCS volume conductor model than the resistor network model (Table 3).

Contact Configuration and Paresthesia Coverage

Questioning the patients about the area of the paresthesia for each configuration revealed that guarding the cathodes by adding anodes did not influence the therapeutic range (discomfort threshold/V_{PT}) or the paresthesia area in a predictable way. Although 2 patients hardly experienced any change in paresthesia attributable to altered contact configurations, most patients mentioned changes in the area where paresthesia was felt. However, in contrast to the expectations, the areas indicated by the patients were not necessarily larger when anodes were added. Moreover, an increased therapeutic range when stimulation was applied with a narrow bipole instead of monopolarly, as predicted by Law (9), has not been found either.

TABLE 2. Patient characteristics[a]

No.	Age(y)/sex	Pain syndrome	Position of cathode(s)	SCS (y)	Pain relief effect of SCS (%)
1	43/F	CRPS	C3–C4	7	90
2	68/F	DNP	T9–T10	3	85
3	46/M	DNP	T10–T11	3	80
4	73/M	DNP	T10–T11	3	70
5	61/M	DNP	T10–T11	3	75
6	75/M	DNP	T11–T12	3	65
7	66/F	FBSS	T9–T10	11	80
8	49/M	FBSS	T9–T10	15	90
9	73/M	DNP	T10–T11	2	85
10	49/M	DNP	T10–T11	2	90

[a] SCS, spinal cord stimulation; CRPS, complex regional pain syndrome type I; DNP, diabetic neuropathic pain; FBSS, failed back surgery syndrome.

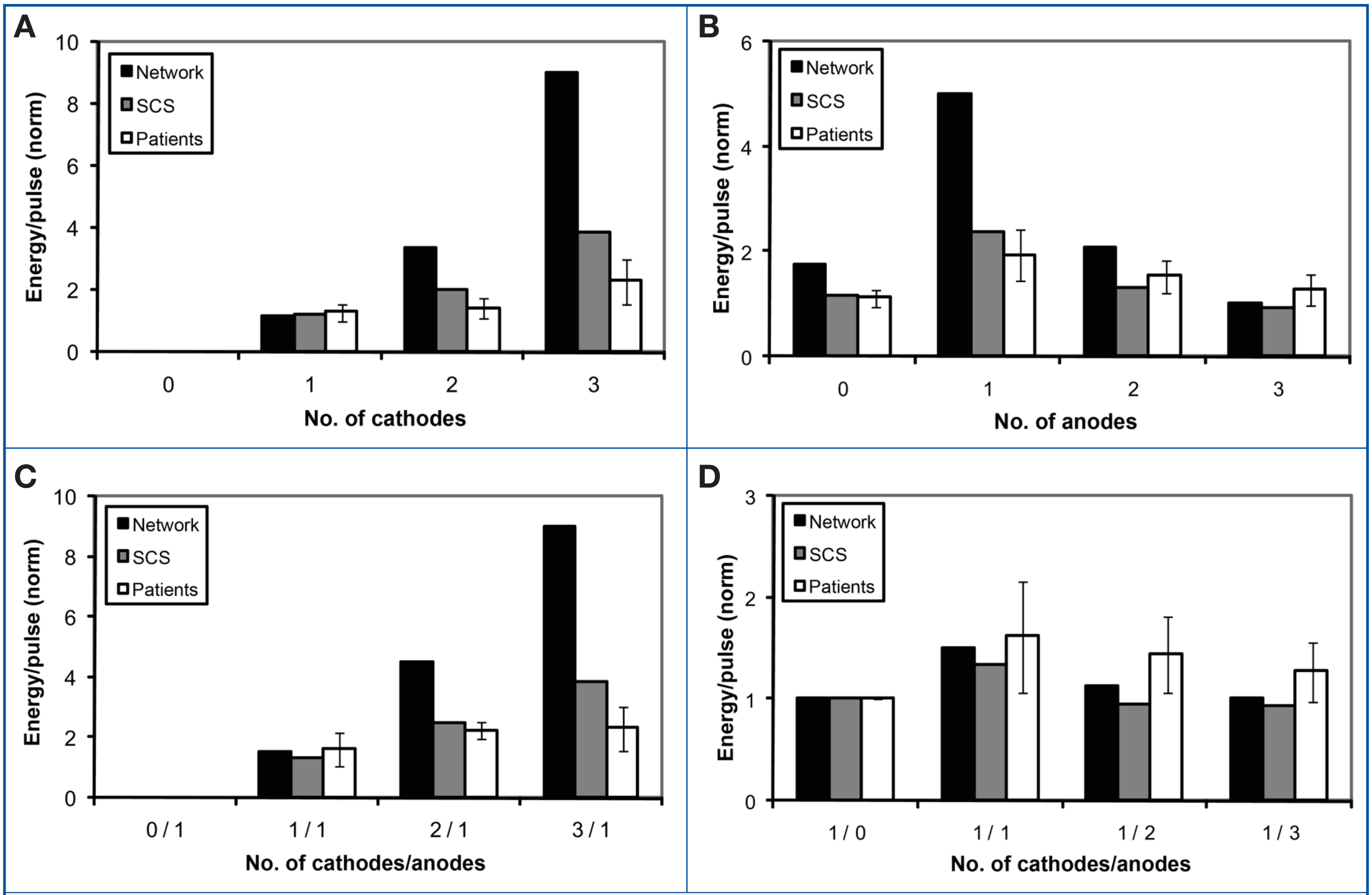

FIGURE 3. *Modeled and empirical maximum tolerable energy per pulse as a function of the number of cathodes (***A***) and anodes (***B***) in the various stimulation configurations. All energy values are normalized to the value of the monopolar configuration. The energy values of all configurations with the same number of cathodes or anodes are averaged and the empirical data for all 10 patients are averaged as well. When the configurations are not averaged, the number of anodes is kept constant and only the number of cathodes is varied (***C***); when the number of cathodes is kept constant and only the number of anodes is varied (***D***), a similar pattern is found. SCS, spinal cord stimulation.*

DISCUSSION

Study Hypotheses and Validation

In this study, we tested the hypotheses that an increase in the number of cathodes in a contact configuration increases E, whereas an increase in the number of anodes decreases E. The hypotheses have been tested in a clinical study, theoretically with a simple resistor network, and by a realistic 3D volume conductor model. Ideally, the outcomes of both models would reliably predict the relevant aspects of the empirical results. If so, future analysis could be done using the simple model only.

Theoretically, we concluded that E was increased when the number of cathodes was increased from 1 to 3. Conversely, E was decreased when the number of anodes was increased from 1 to 3. However, when the number of anodes was further decreased from 1 to 0 (monopolar cathodal stimulation), E was decreased as well. These model predictions are in accordance with the results of the empirical study. Despite the small sample size (10 patients), the empirical data show a statistically significant correspondence with the modeled data, except for the difference in E between 1 and 2 cathodes, which was in accordance with the modeled data but not statistically significant. In 4 patients, the energy required for the 2-cathode configurations was actually lower than for the single cathode. The effect of additional cathodes on E exceeds the effect of additional anodes.

According to the model assumptions, the current needed for threshold stimulation with a cathode is constant; the E_{MT} is proportional to Imp and the current needed for threshold stimulation (Equation 2). The low E_{MT} in monopolar cathodal stimulation is attributable to the low Imp of this configuration compared with bipolar stimulation. The configurations in Figure 3A have 1, 2, or 3 cathodes. For each cathode to be effective, i.e., exciting fibers, it should deliver at least the threshold current. This is shown for E of the network model, which increases more than 7-fold from 1 to 3 cathodes. E, calculated from the

TABLE 3. Energy consumption calculated with the network model and the spinal cord stimulation volume conductor model and empirical values for all patients, their average, and standard deviation[a]

	Network model	SCS model	Energy consumption for each patient										Patient average (SD)
			1	2	3	4	5	6	7	8	9	10	
Cathodes													
1	1.16	1.20	1.21	1.00	1.21	1.14	1.85	1.42	1.33	1.63	1.03	1.03	1.28 (0.28)
2	3.33	2.02	1.46	1.75	1.62	0.98	1.52	0.89	1.40	1.13	1.69	1.75	1.42 (0.32)
3	9.00	3.83	3.13	1.52	3.29	2.03	2.08	1.85	3.29	1.22	2.21	2.36	2.30 (0.73)
Anodes													
0	1.75	1.41	0.91	1.39	1.31	0.99	0.94	0.94	1.20	1.06	1.23	1.15	1.11 (0.17)
1	5.00	2.37	2.76	1.10	2.12	1.62	2.40	1.51	2.37	1.60	1.98	1.89	1.93 (0.50)
2	2.06	1.29	1.65	1.34	1.58	1.18	1.99	1.79	1.36	1.88	1.05	1.43	1.53 (0.31)
3	1.00	0.93	1.51	0.98	1.23	1.14	1.80	1.34	1.45	1.40	0.89	0.87	1.26 (0.30)

[a] SCS, spinal cord stimulation; SD, standard deviation. All energy values are normalized to the value of the monopolar configuration; configurations with the same number of cathodes or anodes are averaged.

SCS model and patient measurements, however, only increased by a factor of 3.2 and 1.8 from 1 to 3 cathodes, respectively.

Volume Conductor Versus Resistor Network Model

The substantially smaller increase in the E_{MT} in the patients and the SCS model relates to the 3D volume conductor properties and the rather small distance of 2 cathodes when connected to adjacent contacts of the SCS lead (Table 1, configuration 3). In the SCS computer model, each anode or cathode creates a 3D electrical field according to the Poisson equation in the surrounding anatomic structures. When active contacts are far apart, these fields do not influence each other, but when contacts are close, they do. As an example, 2 nearby cathodes will create a stronger field than a single cathode; as a result, the required E_{MT} is less than twice the energy needed for a single cathode. This difference was indeed found between the results of the empirical study and the SCS modeling study on the one hand, and the results of the resistor network model on the other. The superposition of cathode fields and thus the decrease in threshold voltage will be less pronounced when the cathodes are at a greater distance.

The resistor network model has no geometry and obeys Ohm's law (the simple form of the Poisson equation). Each contact is represented by a resistor that is given the same value as the corresponding 3D contact Imp, and the same voltages are imposed. Differences in the output parameter E_{MT} caused by systematic differences in model parameter values disappeared by the normalization of the output data. The main difference left between the models is the effect of contact distance, which only exists in the 3D model. It can be concluded that the resistor network model can be used to predict several features of SCS, but is too simple to predict volume conductor properties.

Clinical Aspects

The current study builds on that of North et al. (13), who showed that energy consumption is increased when cathodes are added to a contact configuration but did not analyze the effect when anodes were added. North et al. correctly state that for a given voltage setting, additional contacts increase the current drain. However, stimulation of a neural target is primarily related to the injected cathode current. When an extra contact is added to a configuration, the Imp will be decreased. When the additional contact is an anode, the current to obtain a similar clinical effect as before has to be decreased by decreasing the stimulation voltage and, thereby, the energy consumption. When the additional contact is a cathode, the current will be split into 2 cathode currents. Because each cathode current will be less than the initial current, the stimulation current has to be increased by increasing the stimulation voltage and, thereby, the energy consumption.

Although the empirical measurements were carried out in patients with an Itrel III voltage-controlled IPG that does not deliver a perfect square pulse, this probably did not affect the results as presented because both empirical and modeled data were normalized before being compared.

The differences in energy consumption between actual patients are much larger than predicted in the models. This is primarily due to the fact that, for example, the 3D model has just one set of parameters, but the patients all have different anatomic characteristics. In particular, the thickness of the dorsal CSF layer, which varies greatly among patients (5), has a strong influence on E as well as the Imp of the individual lead contacts. Moreover, in contrast to the 3D model, the lead position is not perfectly symmetrical in patients. Although all modeled contacts have identical Imp values, the Imp of the contacts in the patients and, thus, the corresponding current and E will generally differ.

Besides the technical limitations, the patients' underlying causes of chronic pain may have altered their perception, giving rise to additional variation in the current needed. Furthermore, even though we used the set of configurations that was most similar to their personal stimulation settings, measuring several different configurations can be demanding for the patients.

Preferred Cathode-Anode Configurations

Theoretically, the paresthesia area should be larger with a narrow bipole or a guarded cathode than with just a cathode because these configurations would improve stimulation of the dorsal columns at the expense of dorsal roots (6, 7, 14). Law (9) showed empirically that stimulation with a narrowly separated longitudinal bipole was superior to monopolar stimulation and stimulation with a wide bipole, regarding the therapeutic range and paresthesia coverage in patients with low back pain. North et al. (11) showed a statistically significant preference for a longitudinal guarded cathode. Among all 50 combinations of a 4-pole lead, guarded cathodes were disproportionately preferred by patients with a complex pain syndrome. Instead of the statistically expected 14% of the 62 patients included in the study, a guarded cathode was selected as the best one by 29%. Although the guarded cathode most probably provides the largest paresthesia coverage, a majority of 71% still prefers another configuration, most likely providing an improved coverage of the pain area with paresthesias. Stimulation with a narrow-guarded cathode or a narrow bipole is probably a good initial guess, although the optimal configuration for an individual patient will generally be slightly different.

Empirically, guarding the cathodes did not influence the paresthesia area in a predictable way, which is in accordance with the stochastic nature of this relationship. Although most patients mentioned changes in the area where paresthesia was felt, the area indicated by a patient was not necessarily larger when anodes were added. In some cases, the altered paresthesia areas even caused an uncomfortable or undesirable sensation.

Although adding anodes will decrease energy consumption, therapeutically it is not always favorable for the individual patient. According to North et al. (13), a trade-off between therapeutic effect and energy saving has to be made. When little difference in therapeutic effect exists between 2 contact configurations, but when one is substantially more energy saving, it may be beneficial for the patient to use the configuration that is second best therapeutically.

Programming interleaving pulse trains greatly increases the flexibility in paresthesia coverage and, at the same time, increases energy consumption because the total number of pulses per second is increased. However, this SCS method has not been incorporated in our study, primarily because the IPG we used (Itrel III) does not allow this method.

When stimulation is applied with dual leads and 8 contacts each, the number of active contacts (anodes and cathodes) is usually not substantially larger than with a single quadripolar lead. Alo et al. (1) analyzed the contact configurations in 62 patients with dual leads and reported a mean of 5 contacts (2 cathodes and 3 anodes). In 40% of the patients, the best configuration was 1 or 2 bipoles, and in 48%, 1 or 2 guarded cathodes on adjacent contacts of both leads. Therefore, it is expected that the results of our study are also valid for dual-lead stimulation with 16 contacts.

CONCLUSION

The hypotheses that an increase in the number of cathodes in SCS increases energy consumption and that using more than 1 anode decreases energy consumption have been confirmed by both the empirical and theoretical studies. This implies that when the paresthesia area can be covered with several configurations, it can be beneficial for the patient to program a configuration with only 1 cathode and either 0 or several anodes.

Disclosure

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COMMENTS

The latest study from the University of Twente adds to our understanding of efficient and selective stimulation of the spinal cord. Although the availability of rechargeable power systems has largely mitigated the immediate problem of battery depletion, newer systems may increase power demands, for example by interleaving pulse trains and using novel contact geometries (1). Measures to improve efficiency and to guide rational system design and adjustment are of fundamental importance, and this is a welcome contribution.

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1. North RB, Kidd DH, Olin J, Sieracki JM, Boulay M: Spinal cord stimulation with interleaved pulse trains: A randomized, controlled trial. **Neuromodulation** 10:349–357, 2007.

In this study, de Vos et al. continue to build on their longstanding work in modeling the physiological effects of electrical spinal cord stimulation. Previous work by Holsheimer's group has used finite element modeling to determine optimal electrode contact configurations for the stimulation of the dorsal midline of the spinal cord.

The current study examines energy consumption in spinal cord stimulation as it relates to the patterns of electrode activation. Two theoretical models were used, and the results were compared with clinical information from a set of 10 patients. On the basis of their mathematical models, the authors conclude that power consumption is increased with the number of activated cathodes and is reduced by increasing the number of anodes. Monopolar stimulation has the lowest power consumption, both theoretically and practically.

The findings of the model analysis make sense, since impedance decreases with the anode surface area. Increasing the number of cathodes raises power consumption, since every cathode is responsible for injecting current. Even without a sophisticated knowledge of electrical engineering, one would have little difficulty in accepting these conclusions. However, since the authors do not adjust for the perceived effect of an increased number of cathodes, the practical implications of their theoretical work are not clear. A greater number of cathodes would likely cause a greater perceived effect by the patient, so that it would be difficult to compare different configurations in different patients. Perhaps it is this clinical variability that underlies the lack of a dramatic difference in power consumption among the patients they studied. Still, the conclusion of the article, that programs should try to achieve the most therapeutic stimulation with the least number of cathodes, is supported by the data and makes sense.

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The present work by de Vos et al. uses both modeling and empirical tests of spinal cord stimulators in situ to test the hypothesis that additional cathodes increase energy usage, whereas increasing anodes decreases power use. Both modeling and observation support these hypotheses. The role of anodes in power consumption is controversial, and previous investigators have taken a different view. Nonetheless, the rigor of the current focused exercise is compelling.

The importance of this article derives from the fact that efficient use of power for analgesia should lead to longer battery lives. Each battery change carries the principal risk of infection or lead disruption, as well as substantial cost. Nonetheless, it seems unlikely that the most effective electrode configuration will not be used, despite its energy profile. Thus, the present findings will most likely be applied in cases in which 2 configurations have relatively similar ability to provide analgesia.

The current experiment examines power usage in Itrel batteries with Pisces-Quad electrodes (Medtronic, Inc., Minneapolis, MN). Presumably, the modeling is not wedded to a specific brand or type of implantable pulse generator or electrode. It would be nice, however, to see an expanded study that addresses newer implantable pulse generators and electrodes as well as those made by different manufacturers.

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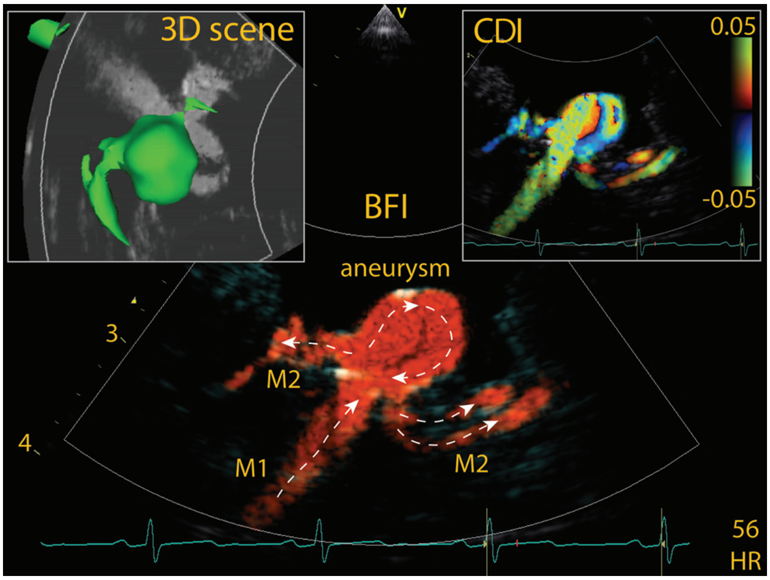

Imaging of a cerebral aneurysm. Before clipping of the aneurysm. The dashed arrows indicate the direction of speckle movement in the blood flow images. The corresponding color Doppler (CDI) images and synchronized navigation scene are shown in the upper right and left corner, respectively (see Video, Supplementary Digital Content 3, http://links.lww.com/A1360). 3D, 3-dimensional; BFI, blood flow imaging.