Mapping of sensory responses to epidural stimulation of the intraspinal neural structures in man

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A database is presented of sensory responses to electrical stimulation of the dorsal neural structures at various spine levels in 106 subjects subjected to epidural spinal cord stimulation. All patients were implanted for chronic pain management and were able to perceive stimulation in the area of pain. All patients entered in this study were able to reliably report their stimulation pattern. Several patients were implanted with more than one electrode array. The electrode arrays were placed in the dorsal epidural space at levels between C-1 and L-1. The structures that were likely involved include the dorsal roots, dorsal root entry zone, dorsal horn, and dorsal columns. At the present time, exact characterization of the structure being stimulated is possible only in limited instances. Various body areas are presented with the correspondent spine levels where implanted electrodes generate paresthesias. Areas that are relatively easy targets for stimulation are the median aspect of the hand, the abdominal wall, the anterior aspect of the thigh, and the foot. Some areas are particularly difficult to cover with stimulation-induced paresthesias; these include the C-2 distribution, the neck, the low back, and the perineum.

**Key Words** - epidural stimulation • neurostimulation • paresthesia • spinal cord stimulation • sensory mapping

The goal of this study was to establish a correlation between spinal levels of implanted epidural electrodes and paresthesias elicited by stimulation of the dorsal intraspinal neural structures. Our purpose was to provide physicians performing epidural spinal cord stimulation with guidelines relating patterns of stimulation-induced paresthesias with spine levels of implanted electrodes. Detailed knowledge of these relations has allowed us more consistently and successfully to place epidural electrodes at the desired spine levels.

This work represents our experience with 106 consecutive patients for whom data were systematically collected and analyzed. To our knowledge, this type of information is not currently available in the literature. There have only been reports of sporadic observations with few patients. Further analysis of the data will provide insight into the physiological mapping of the dorsal spinal cord and related structures.

**Clinical Material and Methods**

*Patient Population*

Data from 106 patients were systematically collected and analyzed. There were 52 men and 54 women, ranging in age from 19 to 73 years. All patients were implanted for chronic pain management and were able to perceive stimulation in the area of pain and to reliably report the stimulation pattern. All electrode arrays* were placed epidurally on the dorsal surface of the spinal cord. Several patients were implanted with more than one electrode array.

*Surgical Procedures*

Seventy-three patients underwent implantation in the thoracic spine. With the patient under local anesthesia, the electrode arrays were placed in the dorsal epidural space through a small laminotomy basically limited to removal of the lower two-thirds of the spinous process, the ligamentum flavum, and (when required) the immediately surrounding bone. Extensive intraoperative testing was performed to assure correct placement of the electrode.

Implantation in the cervical spine was performed in 33 patients. There were two separate implant strategies. For patients with pain in the third division of the trigeminal nerve or in the C-2 distribution, one or two electrode arrays were introduced in a caudal direction

*Resume electrodes manufactured by Medtronic, Inc., Minneapolis, Minnesota.*
under the arch of C-1 (Fig. 1), allowing placement of the electrode in the epidural space under the arch of C-1 and the upper one-third of the C-2 lamina. For patients with pain in the upper extremity/shoulder, the electrode array was implanted at the C5-6 or C6-7 interspace. Because the patients were able to flex their necks, partial spinous process removal was not always necessary. The electrode array was directed rostrally and placed so that it corresponded to the C3-5 vertebral levels. When indicated, a caudally directed electrode array was introduced through the same laminotomy, usually resulting in placement at T1-2. Implantation of electrodes below the C-2 level was performed with the patient under local anesthesia and intravenous sedation. Electrode array placements at the C1-2 level were performed with the patient under general anesthesia in the prone position.

Testing and Data Collection

In all patients who had an Itrel I pulse generator implanted as well as in patients who had more than one electrode array implanted, the arrays were externalized in order to allow testing in the postoperative period. Testing was carried out through an external pulse generator or transmitter. All bipolar and unipolar combinations among electrodes in the implanted arrays were tested. These included testing across contacts belonging to different arrays when more than one array was implanted. Each patient was tested for 3 to 7 days, depending on the number of combinations and on the patient’s cooperation. In a more recent series of patients studied since the introduction of the Itrel II pulse generator,† most had the complete equipment (electrode array and pulse generator) implanted in one sitting.

For the purpose of data collection, an initial evaluation was performed with standard parameters, including rectangular monophasic pulses at a rate of 50 Hz and a pulse width of 210 μsec. The voltage was gradually increased in 0.1- to 0.25-V increments. The distribution and intensity of the paresthesias and the eventually triggered motor contractions were noted.

For data collection, the body surface was divided into 108 areas (Fig. 2). For data analysis, some areas were merged to reduce the total to 20 areas, corresponding to the main parts of the body to which pain is usually referred in the clinical setting. All data were entered in a computer database. Following the initial testing phase, the parameters were adjusted according to individual requirements in order to obtain the best therapeutic results.

Data Analysis

The data reported in this paper include only those from the initial standardized evaluation described above. Our data refer not to single electrode arrays, but rather to the individual contacts within the arrays. This stems from the fact that, with multicontact electrodes, the range of the contacts spans more than one spinal level. The position of the electrode array does not therefore allow precise identification of the stimulated area. For this study, only bipolar and unipolar combinations were analyzed, although tripolar and quadripolar combinations were also tested when indicated. We considered only the position of the contacts when they functioned as cathodes since the cathodal current is the prevalent factor affecting the flow of the stimulation. As demonstrated in our previous work, the role of anodal current is much smaller, although not insignificant.7

A total of 3897 combinations were collected and analyzed. Of these, 738 were in the cervical region and 3159 in the thoracic/L-1 area. There were 3000 bipolar combinations and 159 unipolar. In this study, we did not try to assess differences between unipolar and bipolar groups.

Our database contains data for electrodes implanted at all spine levels between C1-2 and L-1. In order to assure statistical significance for this study, we considered only spine levels containing at least 100 combinations. The levels from C-7 to T-5 contained less than 100 combinations each and were therefore omitted. Future updates of our database will contain statistically significant figures for those levels as well. The data analysis reported in this work therefore refers to 3549 combinations, of which 738 were from contacts located between C1-2 and C-6 and 2811 between T-6 and L-1.

This level of the cathodes of each combination was derived from plain spine x-ray films. For the thoracic spine, the anteroposterior projection was found to be the most accurate. For the cervical spine, we relied on the lateral view.

We also analyzed the position of the cathodes in the spinal canal in a mediolateral direction on plain x-ray films and computerized tomography (CT) scans. The

† Itrel pulse generators, Models I and II, and Xtrell transmitter manufactured by Medtronic, Inc., Minneapolis, Minnesota.
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Fig. 2. For data collection, the body surface was divided into 108 areas where stimulation-induced paresthesias were perceived (left). Data were then entered into a computerized database. For data analysis, the 108 areas can be analyzed individually or can be summarized into 20 body areas (right).

Fig. 3. Graph showing the number of combinations at each spine level. The spine level of a combination is defined by the position of the contact acting as a cathode. Midline cathodes are those placed within 3 mm of the radiological midline; laterally placed cathodes are more than 3 mm from the radiological midline. The largest number of combinations is at the T-10 level. In the cervical area, midline and laterally placed cathodes are equally represented. In the thoracic area, most of the cathodes are placed in the midline.

distance from the radiological midline to the center of the contact was measured with the appropriate correction for magnification. The contacts were divided into two groups: the ones located within 3 mm of the radiological midline and those located more than 3 mm from the midline. In the cervical area, the cathodal positions were equally distributed between midline and lateral location. In the thoracic area, there was a large preponderance of midline-placed contacts. Figure 3 shows the absolute number of combinations at each spine level. The raw data are available on request.

The topographical distribution of the paresthesias was assessed at a threshold where the stimulation was felt by the patient as a strong sensation. These data, therefore, reflect a distribution close to the largest area of obtainable paresthesias in each individual. Ideally one would want to have the same mapping for the initial perception and for the threshold where the stimulation overlaps the painful area. These data are being analyzed and will be the subject of future publications.

To obtain a map that links the cathode positions on the spinal cord to the body surface areas where paresthesias could be perceived, we devised a formula to measure the effectiveness of eliciting sensation in various body parts by positioning the cathode on a specific spine level: effectiveness = (number of combinations at spine level eliciting paresthesias × 100)/total number of combinations at the spine level. The following example demonstrates how the formula works. Suppose there are 82 combinations tested at a cathode position at C-6. If 36 elicited stimulation in the lateral arm, then the effectiveness is 43.9% (36 × 100)/82. Each cathode stimulates multiple areas of the body. If 60 combinations also triggered paresthesias in the hand, we can conclude that, with a cathode on C-6, there is a 73.2% rate of effectiveness for stimulation to the hand and a 43.9% effectiveness rate for stimulation to the lateral arm.

Results

The charts in Fig. 4 detail the distribution of paresthesias perceived in various areas of the body surface after electrode stimulation. Only the salient features of the results are presented below.
FIG. 4. Graphs showing the distribution of stimulation-induced paresthesias according to the 20 summarized body areas. All electrodes were placed in the dorsal epidural space. The distribution of the paresthesias was obtained with a stimulation of 50 Hz and an amplitude setting where the paresthesias were felt as a strong sensation. Only spine levels with at least 100 combinations were considered; therefore, levels C-7 through T-5 were omitted. The percentage is not related to all analyzed combinations, but only to the combinations with cathodes located at the specified spine level. For formula, see text.

The C-2 Area

The C-2 distribution covers the ipsilateral posterior occipital area and the angle of the jaw. The C-2 contribution to the angle of the jaw and the mandible is variable. In some individuals, it covers only a small portion of the angle of the jaw; in others, it covers a large portion of the mandible, almost reaching the midline. The C-2 distribution never overlaps significantly with the sensory distribution of the second division of the trigeminal nerve. Paresthesias in the C-2 distribution were obtained with the electrode placed under either the arch of C-1 or the lamina of C-2. The
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electrode has to be placed slightly off-midline on the affected side. An excessively lateral placement stimulates the nerve root and generates undesirable motor contractions. In our experience, the best arrangement to obtain paresthesias in the C-2 distribution was to have two electrodes side by side at C1–2, one at the midline and one about 3 mm off-midline (Fig. 1). The preferred direction of current was between two adjacent contacts, with the cathode belonging to the laterally placed electrode. Other electrode arrangements might not yield as consistent a stimulation in the C-2 distribution; this explains why in our database only a small percentage of combinations located at C1–2 stimulated the C-2 area (Fig. 4).

The Neck

Neck stimulation is fairly difficult to obtain. The cathode must not be placed below C-3. Optimal stimulation is usually obtained at the C1–2 spine levels. No major differences were found between midline and lateral contacts.

The Shoulder

To stimulate the shoulder, the cathode has to be located at the C2–4 level. Below the C-4 level, shoulder stimulation is found erratically and the coverage is usually not satisfactory. Even with proper placement, shoulder stimulation is not obtained as consistently as other areas, such as the hand.

The Hand

Stimulation of the median aspect of the hand is elicited from a large percentage of combinations with electrodes placed in the cervical area, irrespective of the level. We have observed combinations with cathodes at C-1 giving rise to paresthesias felt uniquely in the ipsilateral thumb. The ulnar side of the hand is not stimulated as consistently and is often stimulated concurrently with the median side. To obtain optimum stimulation of the entire hand, the electrode should be placed at C5–6. Although not represented in this database, stimulation in the hand from electrodes placed as low as T-6 has been observed.

The Chest/Abdominal Wall

Stimulation of the chest/abdominal wall is seldom sought intentionally. In most instances, it is viewed as an undesirable side effect of stimulation directed to other parts of the body, most frequently the low back. Chest wall stimulation is often perceived as an unpleasant constrictive band. Both sensory and motor activation are often obtained at the same threshold, denying any therapeutic effect of the stimulation. Stimulation of the chest/abdominal wall, unfortunately, is a prominent feature of stimulation through electrodes placed in the thoracic spine. Strict midline placement can minimize but not eliminate it. Even with a perfect midline electrode placement, over time, chest/abdominal wall stimulation might become the most prominent feature. A larger percentage of contacts stimulating the chest/abdominal wall were located laterally.

The Anterior Thigh

Stimulation of the anterior aspect of the thigh is very frequently achieved with electrodes placed at the T11–12 spine level, especially if located slightly laterally. This type of stimulation could be attributed, in some instances, to direct stimulation of the L1–3 dorsal roots as they are laterally grouped in the spinal canal at that level. Anterior thigh stimulation due exclusively to activation of the dorsal column fibers can be obtained with electrodes placed at T7–8 or higher.

The Posterior Thigh

Selective stimulation of the posterior aspect of the thigh can be accomplished with electrodes placed at the T11–L1 level. In this instance, stimulation is most likely due to activation of the S-1 dorsal root fibers, which constitute a large medially located bundle, or of the S-1 dorsal root entry zone (DREZ), which is located at the L-1 spine level in most individuals. A larger percentage of contacts were located at the L-1 spine level in most individuals. A larger percentage of contacts were located in the midline. This parallels the trend for the buttck and the posterior aspect of the leg and confirms that the stimulation in this instance is most likely due to activation of the DREZ or the dorsal root.

The Foot

The foot is one of the body areas that displays the highest likelihood of being covered by stimulation-induced paresthesias. An electrode placed in the lower thoracic/upper lumbar area has a 70% effectiveness rate in activating the foot fibers. This rate reaches almost 100% when the cathode is placed at the L-1 spine level. Foot fibers can also be more easily activated from higher spine levels. We have seen several instances of perfectly midline-placed cervical electrodes where the stimulation was initially felt in the sole of the feet. Paresthesias reaching the foot, of course, do not always mean complete coverage of the painful area. Foot stimulation obtained from an electrode placed at L-1 might be more selectively perceived in the sole of the foot and not in the ankle. Further data are necessary to allow for a more accurate prediction of electrode stimulation.

The Perineum

The perineum is difficult to stimulate. Only a very small percentage of combinations elicit paresthesias in the perineum/genitalia, and most of them come from electrodes located at T11–L1. To enhance the possibilities of stimulating this area, the electrodes have to be located at the midline. Of the combinations that elicited paresthesias in the perineum, a strikingly larger percentage were located at the midline. Stimulation is also often simultaneously perceived in the anterior thigh area.

The Low Back

It is very difficult to stimulate the low back only, without intervening chest/abdominal wall stimulation. By overlapping the stimulation curves pertaining to the above structures, the following factors can be identified:
The peak curve for low-back stimulation coincides with the peak curve for the chest/abdominal wall, and the peak in the laterally placed contacts at T-6 and the 0 value at T-7 are probably artificial due to the small number of combinations at those levels; 2) the chest/abdominal wall region has a higher percentage of stimulation than the low back; and 3) the chest/abdominal wall area has a lower stimulation threshold than the low back. All of these factors contribute to the challenge of being able to direct stimulation selectively to the low back without interference from the body walls. In our experience, the best location was at about T9–10, with an electrode placed strictly at the midline. New electrode configurations are being developed that might allow a more exclusive activation in the low-back fibers.

The Buttock

The buttock area can be activated more easily than the low back. This is most likely due to the fact that the peak for the buttock is lower in the spine than the peak for the abdominal wall; therefore, abdominal wall stimulation does not interfere with buttock stimulation. The buttock area still has a substantial representation at T11–L1. The usual pattern of stimulation with an electrode placed at T11–12 is activation first in the posterior leg fibers, then in the posterior thigh, and last in the buttock. We have never encountered isolated stimulation of the buttock area without prior involvement of the posterior aspect of the lower extremity. If the electrode is placed high enough in the spine, stimulation spreads to the low back following activation in the buttock area.

Discussion

Electrical stimulation of the spinal cord for therapeutic purposes has been performed since the early 1970's with variable success.1-5,7,9,13,16-18 Exact electrode positioning in the spinal canal is a key factor in providing successful stimulation. Unfortunately, there are no published guidelines to intraspinal electrode placement backed by a substantial number of observations in a large series of patients. This contrasts with the detailed observations obtained systematically during stereotactic procedures on the thalamus and related structures.10,17,19 The pioneering work of Law and Miller11,12 showed that objective recording of paresthesias and documentation of electrode position is essential for successful neurostimulation. Our efforts have been directed to developing a growing database of responses to electrical stimulation of the neural intraspinal structures at various spine levels.6 All testing and data collection were performed by a limited number of professionals working full-time in our neurostimulation program and with standardized electrical parameters. This minimized deviations from the protocol and assured a high degree of uniformity and reliability in the collected data.

Stimulated Structures

Initially, the term “dorsal column stimulation” was applied to this procedure, with the assumption that most, if not all, of the observed effects (paresthesias and pain relief) were attributable to direct stimulation of the dorsal columns. More recently, however, it has become clear that applying an electrical field to the dorsal epidural space might activate a larger number of neural structures. We believe that our data reflect paresthesias elicited from epidural stimulation of various intraspinal neural structures both inside and outside the spinal cord. Because the paresthesias were always ipsilateral to the stimulating electrodes and were perceived as a tingling sensation, we believe that our data reflect stimulation of large afferent myelinated fibers. The most likely involved structures include the dorsal columns, dorsal roots, DREZ, and dorsal horn.

On a clinical basis, distinction between stimulation of a dorsal root versus a dorsal column is feasible, although not always possible. A segmentary distribution of paresthesias with a low electrical threshold and early motor recruitment is indicative of stimulation of a dorsal root in the lateral gutter of the spinal canal. A widespread distribution of paresthesias with bilateral involvement and a slightly higher threshold is more indicative of activation of the dorsal columns. Stimulation of the DREZ or dorsal horn should give a pattern that resembles that of the corresponding nerve root. The problem of distinguishing stimulation patterns is even more complex because more than one structure is often simultaneously stimulated. A typical example is when the electrodes are placed at the T11–L1 level. At this level, the nerve roots of the cauda equina come in very close contact with the spinal cord and follow it for a distance of several centimeters. In this area, it is common to have a mixture of dorsal column/dorsal root stimulation; therefore, it might be practically impossible to differentiate them on a clinical basis. Another conflict occurs when the electrode is placed 3 to 4 mm from the midline and could simultaneously stimulate the dorsal column, dorsal root, and corresponding DREZ.

We can therefore conclude that the data presented reflect the sensory equivalents of electrical activation of the dorsal root/dorsal column complex at various spine levels. At the present time, no further characterization of the data is possible. One could assume that contacts placed within 3 mm of the radiological midline elicited more responses from the dorsal columns, whereas paresthesias triggered from laterally placed electrodes were more likely to originate from the dorsal roots. Although this view can be subjected to criticism, in a general form it holds some practical usefulness for the physician performing electrode implants.

Midline vs. Lateral Placement of the Electrodes

The radiological distance from the midline of each contact was recorded in the database. Because of the variability in x-ray film quality and positioning, we subdivided contact positions into two general groups: those located less than 3 mm from the midline and those located laterally (> 3 mm from the midline). Any further subdivision would be subjected to excessive evaluation error. We assumed that the laterally located contacts most likely reflect stimulation of structures other than the dorsal columns. This distinction, al-
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though not categorical, has a practical usefulness for the physician planning a strategy for electrode placement. In our experience, the most effective stimulation was that elicited from electrodes placed within 3 mm of the midline. In general, midline structures including the low back, buttock, and perineum can be best stimulated with midline-placed electrodes.

Laterality in the position of the electrodes has a variable effect depending on the spine level and on the targeted body areas. For instance, the C-2 area can be reached more frequently when the electrodes are placed laterally. The chest and abdominal wall also can be stimulated more easily with laterally placed electrodes. The upper extremity can be stimulated fairly easily with either midline- or laterally placed electrodes. Naturally, to obtain bilateral paresthesias, the placement has to be as close as possible to the midline. In the lower thoracic spine, laterally placed electrodes more frequently elicited paresthesias in the anterior part of the lower extremity. This contrasts with the posterior aspect of the lower extremity, which was stimulated more consistently with contacts located in the midline.

Rostral vs. Caudal Placement of Electrodes

The data relating to rostrocaudal positioning of the electrodes are presented in Fig. 4 and discussed in the results. As a general comment, the direction of the activated paresthesias usually follows a distribution caudal to the implanted level. Occasionally, paresthesias are experienced in areas cephalad to the electrode. We have seen instances of paresthesias in the upper extremities being perceived from electrodes placed in the midthoracic area. This, however, is not a consistent finding and cannot be relied upon in planning a procedure.

Conclusions

It is possible that, with different electrode arrangements, intercontact distance, and electrical parameters, the distribution of paresthesias can be modified in a more discrete fashion. This might allow us in the future to direct the current flow more precisely and stimulate the desired body areas more consistently.

References
