Intraoperative evoked potentials recorded in man directly from dorsal roots and spinal cord

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Direct spinal cord surface recordings of evoked spinal cord potentials have been made in 26 patients during neurosurgical procedures for intractable pain. Monopolar recordings at the dorsal root entry zone after peripheral nerve stimulation have been made at multiple levels for segmental localization and to monitor the state of the afferent path and dorsal horn. Dorsal root and dorsal column conduction has been tested on diseased and intact sides. Normal afferent conduction velocity was found to have an overall mean of 61.33 m/sec for cervicothoracic and lumbosacral peripheral nerves, and 50 m/sec for the dorsal columns. The normal mean amplitude for the slow negative wave (N₁) recorded at the root entry was 52.54 μV, while that for the dorsal column conducted response recorded within 4 cm of the stimulus point on the dorsal columns was 347.5 μV. Several different placements of stimulating and recording electrodes are described, as well as their application. An interpretation of the resulting data is proposed.

KEY WORDS: spinal cord • evoked potentials • dorsal root entry zone • intraoperative recording • dorsal column stimulation • pain

The recording of standardized evoked electrical potentials from the spinal cord of normal subjects can provide an objective measurement of the functional capacity and interrelationships of the nervous system, and provide a basis for interpretation of abnormal signals which may occur in disease states and in conditions where there is injury to the spinal cord or afferent nerves. With such a base, the site of a lesion can be localized and the extent of the injury or disease process ascertained. It is also important to be able to monitor the functional condition of the spinal cord during neurosurgical procedures. The recording of evoked potentials allows accurate localization of the site of the pathology which is necessary for optimal neurosurgical intervention. It also provides an observation of the continuity and capacity of the spinal cord components after neurosurgical lesions or repairs.

This paper describes the techniques used for the intraoperative recording of evoked potentials and describes the electrical signals recorded from the dorsal roots and spinal cord in normal and pathological states.

Clinical Material and Methods

Clinical Material

We have recorded subdural electrical responses in 26 patients from the dorsal surface of the spinal cord during neurosurgical procedures for intractable pain. Records were made before and after production of the lesions. Thresholds of all evoked responses were determined. The briefest and lowest amplitude stimuli were used for dorsal root and dorsal column stimulation. Monophasic square waves of 0.05 to 0.5 m sec duration were delivered via a Grass S88 stimulation unit and a constant-current isolator at amplitudes of 0.5 to 20 mA. A frequency of 2.3 Hz was used to avoid averaging at frequency harmonics of 60 cycles and because we have
Intraoperative spinal evoked potentials

TABLE 1

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>Cause of Pain</th>
<th>Clinical Findings</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>62, M</td>
<td>fall, 1978: C-6 avulsion</td>
<td>intractable pain, lt arm</td>
<td>C5-6 rhizotomy, 9/16/80; DREZ lt C5-8, 3/10/81</td>
</tr>
<tr>
<td>2</td>
<td>26, M</td>
<td>motor vehicle accident; brachial plexus avulsion, 9/14/80</td>
<td>intractable pain, lt arm, C5-T1</td>
<td>DREZ lt C5-T1, 3/31/81</td>
</tr>
<tr>
<td>3</td>
<td>55, M</td>
<td>fall, 1977: brachial plexus stretch injury</td>
<td>brachial plexus neuropathy, rt</td>
<td>DREZ rt C8-T1, 11/21/80</td>
</tr>
<tr>
<td>4</td>
<td>39, M</td>
<td>GSW, 1977: cauda equina avulsion, 1979</td>
<td>intractable dysesthesia, rt leg</td>
<td>DREZ rt L5-S1, 5/8/81</td>
</tr>
<tr>
<td>5</td>
<td>48, M</td>
<td>industrial accident; lt arm amputated, 1979</td>
<td>phantom limb pain, lt hand</td>
<td>DREZ lt C6-8, 3/27/81</td>
</tr>
<tr>
<td>6</td>
<td>34, M</td>
<td>fall, 1980: T-12 fracture</td>
<td>dysesthetic pain, rt leg; atrophy, weakness</td>
<td>surgical exploration, 8/25/81</td>
</tr>
<tr>
<td>7</td>
<td>42, F</td>
<td>bilateral 1st rib resection, 1976</td>
<td>intractable lt arm pain</td>
<td>DREZ lt C5-T2, 1/20/82</td>
</tr>
<tr>
<td>8</td>
<td>39, M</td>
<td>motor vehicle accident, 1972; below knee amputation, 1976</td>
<td>stump pain, rt</td>
<td>DREZ rt L5-S1, 1/25/82</td>
</tr>
<tr>
<td>9</td>
<td>43, M</td>
<td>GSW, 1958; C-6 cord injury, lt motor vehicle accident, 1979; brachial plexus avulsion</td>
<td>chronic rt arm pain</td>
<td>DREZ lt C-6, 11/18/80</td>
</tr>
<tr>
<td>10</td>
<td>24, M</td>
<td>above knee amputation, 1979</td>
<td>lt arm pain</td>
<td>DREZ lt C4-8, 8/14/81</td>
</tr>
<tr>
<td>11</td>
<td>64, M</td>
<td>motorcycle accident; crush injury, avulsion L1-S1</td>
<td>phantom limb pain, chronic stump pain</td>
<td>DREZ lt L1-5, 10/2/81</td>
</tr>
<tr>
<td>12</td>
<td>32, M</td>
<td>motorcycle accident; crush injury, avulsion L1-S1</td>
<td>phantom limb pain, rt</td>
<td>DREZ rt L1-S1, 11/17/80</td>
</tr>
<tr>
<td>13</td>
<td>40, M</td>
<td>GSW to abdomen, 1975</td>
<td>T-12 paraplegia; bilateral leg pain</td>
<td>DREZ rt T11-L2, 9/26/80</td>
</tr>
<tr>
<td>14</td>
<td>44, F</td>
<td>GSW's, 1978</td>
<td>bilateral anterior thigh pain weakness, all limbs; tingling rt arm &amp; leg</td>
<td>DREZ rt T12-L1, 6/11/81</td>
</tr>
<tr>
<td>15</td>
<td>23, M</td>
<td>cervical meningioma, symptoms, 1971</td>
<td>myelotomy L1-S1, 7/17/80; DREZ bilat T10-L2, 8/21/81</td>
<td></td>
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<tr>
<td>16</td>
<td>23, M</td>
<td>diving accident, 1978: C-6 fracture</td>
<td>quadriaparesis; pain, flexor spasms, both thighs</td>
<td>DREZ rt T12-S2, 1/19/82</td>
</tr>
<tr>
<td>17</td>
<td>49, M</td>
<td>amputation above lt knee</td>
<td>phantom limb pain</td>
<td>DREZ rt T12-L1, 11/76; DREZ rt C7-T1, 1/13/81</td>
</tr>
<tr>
<td>18</td>
<td>45, M</td>
<td>industrial accident; lt ulnar nerve injury, 1976</td>
<td>pain, ulnar distribution; tardy ulnar palsy</td>
<td>DREZ rt T11-S1, 10/6/81</td>
</tr>
<tr>
<td>19</td>
<td>44, M</td>
<td>GSW, transsection, T-12</td>
<td>paraplegia; rt hip &amp; thigh pain weakness, spasticity, sensory disturbance, both legs; bladder &amp; bowel dysfunction</td>
<td>removal of dorsal column stimulator, 1/25/83</td>
</tr>
<tr>
<td>20</td>
<td>56, F</td>
<td>displacement of dorsal column stimulator, 1981</td>
<td>shoulder pain, lt brachial plexitis</td>
<td>DREZ rt C2-5, 11/23/81</td>
</tr>
<tr>
<td>21</td>
<td>33, M</td>
<td>severe electrical injury; bilateral upper arm amputation, 1978</td>
<td>intractable stump pain</td>
<td>DREZ rt L5-S2, 1/29/82</td>
</tr>
<tr>
<td>22</td>
<td>52, M</td>
<td>amputation of rt leg</td>
<td>intractable lt arm pain</td>
<td>DREZ rt C6-8, 3/20/81</td>
</tr>
<tr>
<td>23</td>
<td>26, M</td>
<td>motor vehicle accident, 1980; brachial plexus avulsion, lt C7-8</td>
<td>phantom limb pain, lt leg</td>
<td>DREZ rt S-1, 9/28/81</td>
</tr>
<tr>
<td>24</td>
<td>63, M</td>
<td>amputation of lt leg, 1978</td>
<td>post-herpetic pain</td>
<td>DREZ rt T4-7, 12/14/81</td>
</tr>
<tr>
<td>25</td>
<td>45, F</td>
<td>herpes zoster, lt T-5, 1980</td>
<td>phantom limb pain</td>
<td>DREZ rt C8-7, 8/10/81</td>
</tr>
<tr>
<td>26</td>
<td>39, M</td>
<td>crush injury, lt arm, 1979: amputation</td>
<td>phantom limb pain</td>
<td>DREZ rt C8-7, 8/10/81</td>
</tr>
</tbody>
</table>

* Abbreviations: DREZ = dorsal root entry zone lesion; GSW = gunshot wound.

found that rates above this value reduce the postsynaptic evoked response amplitude at the spinal level. The cathode for the stimulating electrode was placed proximally along the nerve. The polarity of the stimulus was reversed by a switch on the stimulator, and the stimulus that gave the lowest threshold response was used.

Anesthetic Technique

Premedication consisted of 100 mg secobarbital, given intramuscularly 90 minutes prior to induction of anesthesia. Basal anesthesia was induced with thiopental sodium, administered slowly intravenously. The dose was determined as twice the amount necessary to abolish the lid reflex, and ranged from 250 to 1000 mg. Following hyperventilation of the lungs with oxygen, endotracheal intubation was carried out with a cuffed tube. Intubation was performed during muscle relaxation with succinylcholine chloride. A light plane of anesthesia was maintained with nitrous oxide, oxygen, intravenous narcotics (fentanyl), halothane, or etherane. Continuous muscle relaxation was maintained with intermittent doses of either pancuronium or d-tubocurarine. Ventilation was controlled with a mechanical ventilator, using tidal volumes of about 1000 ml. Respiratory rate was adjusted to achieve end-tidal CO₂ concentrations of about 5%. Monitoring included chest and heart sounds via an esophageal stethoscope, electrocardiogram, direct and indirect blood pressures, end-tidal CO₂ concentrations, and intermittent blood gas analyses.
FIG. 1. Technique for recording evoked potentials from the peripheral nerve to the cord dorsum. Four-contact monopolar recording montages, with the active leads connected to the negative preamplifier grids, are shown located on the spinal cord at cervical and thoracolumbar levels. The G2 terminals are ganged together at the preamplifiers and the reference lead is connected to two of the four preamplifiers. The stimuli are bipolar, with the electrode cathode proximal to the anode near to the nerve. The stimulus may be applied consecutively to the peripheral nerves or directly to the dorsal columns or dorsal roots according to surgical requirements.

There were no anesthetic complications; vital signs and acid-base data were maintained within physiological limits in all cases.

**Preoperative Nerve Location and Electrode Placement**

Prior to the actual intraoperative recording, several steps are taken to determine the best location for placement of the stimulating electrodes over the peripheral nerves. Electrodes were placed over the peripheral nerves bilaterally, in identical locations if at all possible. On the evening before surgery, the appropriate nerves were localized and sensory thresholds determined in the awake patient by the report of tingling sensation after transcutaneous stimulation. These locations were marked with a pen. On the day of surgery, these locations were checked again by the same means before the patient was anesthetized.

Once the patient was anesthetized, paired non-polarizable silver needle electrodes were inserted subcutaneously over the nerves, and placement was checked by observing the muscle twitch in the distribution of the particular nerve. The median and ulnar nerves at the wrist were stimulated for C7-8 spinal root analysis. The radial nerve was stimulated at the dorsal wrist between the extensor pollicis longus and brevis tendons (the anatomical "snuff box") to avoid activation of median nerve fibers on the thenar eminence of the hand and to isolate C-6 root input. The posterior tibial nerve, 4 cm distal to the popliteal fossa, and the femoral triangle were stimulated for S-1 and L-2 analysis, respectively. Stimulation of the femoral nerve at the triangle would also activate L3-4 sensory input, although at reduced amplitude relative to L-2. Figure 1 summarizes the electrophysiological arrangement that was used.

**Stimulation and Recording During Surgery**

The method employed for direct recording of evoked potentials on the dorsal surface of the human spinal cord was as follows. A laminectomy was carried out over the site of the spinal cord pathology or at the site of the planned therapeutic lesions. The dura was opened, exposing the subarachnoid space and the dorsal surface of the spinal cord.

After exposure of the spinal cord, recording electrodes were positioned either directly on the dorsal surface of the cord or with a special electrode holder mounted on a Miskimon retractor (Fig. 2). A large grounding pad (standard 3M cautery pad) was placed proximal to the stimulus. This position was used to reduce stimulus artifact and further reduce 60 cycle interference.

The multiple-contact recording electrode (Fig. 2) consisted of two to four platinum-iridium discs, $1.5 \times 2$ mm in size, with 1-cm interelectrode distances. The discs were laterallized in a Silastic-coated Dacron web.
Intraoperative spinal evoked potentials

FIG. 2. Left: Arrangement of stimulating and recording electrodes during a dorsal root entry zone procedure. A bipolar electrode, used for stimulating an intact dorsal root (note avulsion of three roots rostral to this), is held in a ball-and-socket manipulator mounted on a post which is part of the retractor. An Avery plate electrode is positioned for recording cord dorsum or dorsal column responses. Right: Some of the Avery plate electrodes used in recording and stimulating the spinal cord. The spacing of the plates was to facilitate recording from adjacent dorsal root entry zones. In the cervical spinal cord, segments are approximately 1 cm in longitudinal extent. The arrangement of the plates in the uppermost (A) electrode makes possible bipolar stimulation of the dorsal columns using combinations of plates. This electrode can also be used to record bilaterally at two root entry zones. The positioning of the plates, separated by 1 cm within the web, allowed recording at the root entry (B and C) or midline (D). E: Electrode used primarily for bipolar dorsal column stimulation. It was possible to make simultaneous recordings from the root entries of four dorsal roots during peripheral nerve stimulation.

to increase the proximity to the DREZ, and to maximize the recording of the afferent volley component of the cord dorsum potential. Four-channel recording obviated the need for consecutive multiple recordings and provided adequate field representation for differential amplitude and conduction analysis.

During certain procedures, additional recordings were made from two adjacent dorsal roots using silver ball electrodes after peripheral nerve stimulation. Also, two-point recordings using silver ball electrodes on the dorsal spinal cord were sometimes used for analysis of peripheral nerve to dorsal root or dorsal column continuity. If further confirmation of root and spinal electrical function was required, the isolated roots and the dorsal columns were stimulated with four-channel dorsal column recording.

A Miskimon retractor, placed in the surgical site (Fig. 2), has been adapted to serve a dual purpose: as a reference (the indifferent lead, G2) for recording, and as a base for the manipulators that hold the root recording and stimulating electrodes. The retractor was used consistently as the reference and connected to G2(+). The G2(+) inputs are ganged together by connections at the two to four preamplifiers (Fig. 1). A lead to the retractor is connected to amplifier No. 1 at G2. The grounds are also ganged together at the preamplifier. The two to four contacts of the active recording electrode are connected separately to each of two to four preamplifiers at G1(−). The only recording in which this was not the case is presented in Fig. 8. In this case a bipolar recording electrode was placed longitudinally on the cord and the most cranial contact was connected to G2(+), while the caudal contact was connected to G1(−).

The evoked responses were differentially amplified using Grass P15 preamplifiers (×100) with a bandpass of 3 Hz to 10 kHz.* The single end output was further amplified ×1200.† Relatively small signal size and ambient noise dictated summation on a Nicolet 1170 computer of average transients. Eight to 128 repetitions were summated under normal circumstances, but when there was spinal cord pathology and/or consequent attenuation of the signal, more averaging was carried out. With peripheral nerve stimulation, a 6- to 8-msec delay of sweep initiation past the stimulus artifact reduced baseline shift on the display. Artifact reject

* Grass preamplifier, Model P15, manufactured by Grass Instrument Co., 101 Old Colony Avenue, Quincy, Massachusetts.
† Tektronix amplifier, Model 5110, with modified 5A18N amplifier plug-in units manufactured by Tektronix, Inc., Beaverton, Oregon; and Nicolet plug-in amplifier, Model 172-B, manufactured by Nicolet Instrument Corp., Madison, Wisconsin.
TABLE 2
Latencies and duration of components of cord dorsum response as recorded from DREZ*

<table>
<thead>
<tr>
<th>Wave Component</th>
<th>Onset of Latency (msec)</th>
<th>Latency to Peak (msec)</th>
<th>Component Duration (msec)</th>
<th>No. of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1A</td>
<td>1.87 ± 0.43</td>
<td>1.20 ± 0.41</td>
<td>1.20 ± 0.41</td>
<td>10</td>
</tr>
<tr>
<td>N1</td>
<td>1.94 ± 0.61</td>
<td>10.30 ± 1.34</td>
<td>10.30 ± 1.34</td>
<td>17</td>
</tr>
<tr>
<td>N2</td>
<td>4.14 ± 1.10</td>
<td>22.00 ± 10.12</td>
<td>22.00 ± 10.12</td>
<td>2</td>
</tr>
<tr>
<td>P</td>
<td>11.64</td>
<td>62.30</td>
<td>62.30</td>
<td>1</td>
</tr>
</tbody>
</table>

* Values are means ± standard deviations. DREZ = dorsal root entry zone. For explanation of wave components see text.

capability on the averaging computer was adjusted to prevent summation of amplitudes larger than 0.25 mV to reduce ectopic electrical influence from contaminating the recording. The evoked potential display on the averager was photographed from the Nicolet for subsequent analysis.

Results

Cord Dorsum Potentials

Cord dorsum potentials were recorded from the root entry zones of the spinal cord after peripheral nerve stimulation at twice the threshold for the first slow negative potential (N1). For cervicothoracic recordings, the radial, median, and ulnar nerves were stimulated transcutaneously at the wrist; and for thoracolumbar recordings, the posterior tibial, peroneal, and femoral nerves were stimulated transcutaneously adjacent to the popliteal fossa and inguinal areas.

The cord dorsum response, recorded with a monopolar lead at the root entry zone after peripheral nerve stimulation, was found to consist of components that

![Figure 3](image)

FIG. 3. Recordings of the normal cord dorsum response after supramaximal (for N1 amplitude) transcutaneous stimulation of peripheral nerves. The cord dorsum response provides a means for determining the maximal segmental dorsal horn response for each nerve. PAS = primary afferent spike, a compound-action potential in large-diameter afferent fibers in the dorsal column. N1 = first postsynaptic negative wave, showing activity in dorsal horn neurons after one synapse. N2 = second postsynaptic negative wave, showing cellular activity after activation of smaller-diameter myelinated afferent nerve.
Intraoperative spinal evoked potentials could be related to afferent activity followed by those that signaled postsynaptic activity. There was a triphasic spike (primary afferent spike) which is the compound action potential of fibers in the dorsal roots and dorsal column. Following this, a slow negative potential was recorded, on the rising phase of which could generally be observed a small negative elevation which has been termed N1A. The N1A wave is thought to be generated in primary afferent terminals. The subsequent large slow negative waves are due to activity in elements within the dorsal horn. These were followed by a slow positivity. (A fuller description of this is given below, in the Discussion; see also Yates, et al.) Cord dorsum responses obtained from lumbosacral and from cervico-thoracic regions were found to be similar. Table 2 summarizes our observations of the latencies and duration of the components of the cord dorsum response. Latencies are measured from the triphasic afferent spike.

By simultaneous recordings at the entry zones of four adjacent roots after stimulation of a peripheral nerve, it was possible to localize the major spinal cord segment of root entry for that nerve. Table 3 summarizes the mean values for conduction latency and velocity, as well as for the amplitudes of the normal cord dorsum evoked potentials in the major segment of entry. Figure 3 shows normal recordings from the cervical cord segments 11 to 14 msec after stimulation of the intact median nerve and the ulnar nerve. The maximal response, recorded at the spinal cord, for the median nerve was at C-6, while that for the ulnar nerve was at C-8. After femoral nerve and posterior tibial nerve stimulations, the maximal responses were at the L-1 and S-1 spinal cord levels, respectively.

The cord dorsum potential, recorded at the dorsal root entry, gives an indication of the major dorsal root entry for a particular peripheral nerve. The amplitude and conduction velocity of the primary afferent spike are measures of the intactness of the peripheral nerve and dorsal root. The form and amplitude of the negative waves (N1 and N2) indicate the condition of the dorsal horn.

**TABLE 3**

<table>
<thead>
<tr>
<th>Spinal Cord Level &amp; Nerve</th>
<th>No. of Subjects</th>
<th>Site of Maximum Response</th>
<th>Conduction Distance (cm)</th>
<th>Conduction Latency (msec)</th>
<th>Conduction Velocity (m/sec)</th>
<th>Amplitude (μV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cervical radial</td>
<td>4</td>
<td>C-5</td>
<td>79.5 ± 8.20</td>
<td>14.13 ± 0.53</td>
<td>58.80 ± 8.20</td>
<td>26.53 ± 18.28</td>
</tr>
<tr>
<td>cervical median</td>
<td>10</td>
<td>C-6</td>
<td>78.6 ± 6.07</td>
<td>12.13 ± 0.84</td>
<td>66.35 ± 4.69</td>
<td>63.4 ± 25.2</td>
</tr>
<tr>
<td>cervical ulnar</td>
<td>9</td>
<td>C7-8</td>
<td>78.9 ± 7.31</td>
<td>12.40 ± 0.75</td>
<td>65.0 ± 5.24</td>
<td>54.01 ± 27.3</td>
</tr>
<tr>
<td>thoracolumbar femoral</td>
<td>6</td>
<td>L-1</td>
<td>45.2 ± 5.85</td>
<td>7.62 ± 1.36</td>
<td>62.2 ± 5.88</td>
<td>52.7 ± 33.7</td>
</tr>
<tr>
<td>thoracolumbar posterior tibial</td>
<td>8</td>
<td>L-1-S1</td>
<td>77.0 ± 7.81</td>
<td>12.37 ± 4.0</td>
<td>61.6 ± 2.19</td>
<td>66.1 ± 25.3</td>
</tr>
<tr>
<td>thoracolumbar peroneal</td>
<td>1</td>
<td>L-1</td>
<td>73.0</td>
<td>13.5</td>
<td>54.0</td>
<td></td>
</tr>
</tbody>
</table>

* Values are means ± standard deviation.

Intraoperative Stimulation of Dorsal Roots

In certain cases the individual dorsal roots themselves were stimulated, with recordings made near the dorsal root entry from the surface of the dorsal columns. Careful measurements were made of the conduction distance between the stimulating and the closest recording electrode. The inter-electrode distance was known to be 1 cm. Recordings made during surgery in Case 25 are shown in Fig. 4. For this recording, stimuli were applied to the intact right thoracic root, T-4, and monopolar records were made at the dorsal root entry of T4–8. This type of recording represents a compound-action potential from the dorsal root, and can indicate its functional condition (see also Fig. 5). Recordings from Case 10 during surgery for intractable pain are presented in Fig. 5. The left C-5 and C-6 roots (dorsal and ventral) were completely avulsed at the time of an automobile accident 2 years earlier. A small strand of left C-7 dorsal root remained, while the left C-8 dorsal root appeared mainly intact. The cord dorsum responses taken from the intact right side were normal...
both in latency and amplitude, while those from the left avulsed side were prolonged in latency at the C-5 and C-6 spinal cord levels, and all were reduced in amplitude. There was no sign of a presynaptic component except at C-8. The C-8 response was also attenuated in amplitude as compared to the response on the right (80 μV vs. 200 μV), which may indicate that the C-8 dorsal root was not entirely intact, although it appeared normal. Small responses were recorded at all levels and must represent intraspinal conduction. When the partially intact left C-7 dorsal root was stimulated, a potential of 39 μV was generated with a conduction velocity of 25 m/sec. Stimulation of the left C-8 dorsal root and recordings from dorsal columns resulted in a normal response of 359 μV amplitude and a conduction velocity of 50 m/sec (Fig. 5).

The condition of the dorsal columns was tested by suprathreshold stimuli being applied to the dorsal columns with bipolar Avery plate electrodes below the level of denervation and recordings being made on the dorsal columns with two or four monopolar electrodes separated by 1 cm above the area of denervation. Recordings were made on each dorsal column both on the denervated and intact sides, and results compared before and after the production of DREZ lesions. This is shown in records taken from Case 26 (Fig. 6). This patient was suffering from a posttraumatic phantom limb-brachial plexus avulsion syndrome associated with the loss of the left arm. Prior to lesion production, the amplitude of the dorsal column-conducted response was 80 μV bilaterally. Recordings made immediately after the radiofrequency lesions in the left DREZ showed that there was a 50% reduction in amplitude on the left, with no reduction in amplitude on the right. There was no change in conduction velocity, which was 50 m/sec bilaterally.

![Figure 5](image-url)
Intraoperative spinal evoked potentials

Table 4 describes the results of recordings from 15 intact or normal dorsal columns following suprathreshold stimuli to the dorsal columns caudal to the point of recording. A mean conduction velocity of approximately 50 m/sec was similar for the dorsal columns at both cervical and thoracolumbar levels, as was an amplitude of 315 µV.

Conducted Potentials

Bipolar recordings of conducted responses were made from the spinal cord surface over the dorsal columns after peripheral nerve stimulation in certain cases. Figures 7 and 8 show photographs and recordings taken during surgery in Case 15 for the removal of an intradural meningioma at the C1-2 spinal cord level. Initial exposure (Fig. 7 left) revealed compression of the spinal cord and distortion of the dorsal roots C-2, C-3, and C-4 by the tumor. The recording shown in Fig. 8, I-A, was made prior to removal of the meningioma. The dorsal columns were stimulated below the tumor (C-4 spinal level) and recordings were made at the C-1 spinal level rostral to the tumor, showing a small positive potential, preceded by a polyphasic predominantly negative potential with a conduction velocity of 4 m/sec. A negative potential (Fig. 8, I-B) was recorded after tumor removal. Recordings at C-1 and C-4 after median nerve stimulation were obtained prior to tumor removal (Fig. 8, II-A and II-B). The conduction velocity of the potential evaluated by interwave latency analysis, was 55 m/sec up to the level of the tumor, and 4 m/sec through the spinal cord adjacent to the tumor.

The conduction velocity was 30 m/sec up to the tumor, and 4 m/sec through the spinal cord at the tumor level. This dorsal column conduction velocity to posterior tibial nerve stimulation recorded at a cervical level was normal (see Discussion). No records of dorsal column conduction to posterior tibial nerve stimulation were taken after tumor removal. The cervical spinal cord is shown after tumor removal in Fig. 7 right. This patient had no deterioration of neurological status, and indeed showed marked improvement over several months.

However, an improvement of evoked potentials recorded from the cord dorsum does not necessarily augur an improvement in neurological status. In another patient (Case 20), a dorsal column stimulator became displaced and caused spinal cord compression; the conducted activity through the area of arachnoiditis and compression was recorded before and after removal of the stimulator. The cord was stimulated below the damaged area and recordings were made rostrally. The conduction velocity of the signal was unchanged; the amplitude was increased along with a decreased threshold.

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Table 4

<table>
<thead>
<tr>
<th>Spinal Cord Level</th>
<th>No. of Subjects</th>
<th>Conduction Velocity (m/sec)</th>
<th>Amplitude (µV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cervical</td>
<td>6</td>
<td>50.22 ± 4.27</td>
<td>308.48 ± 246.63</td>
</tr>
<tr>
<td>thoracolumbar</td>
<td>9</td>
<td>50.27 ± 4.10</td>
<td>321.13 ± 227.08</td>
</tr>
<tr>
<td>average</td>
<td></td>
<td>50.25 ± 4.19</td>
<td>314.75 ± 236.86</td>
</tr>
</tbody>
</table>

* Values are means ± standard deviation.

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Fig. 6. Intraoperative recordings in Case 26. *Upper Pair:* Dorsal column conducted responses, on the left (A) and the right (B), recorded intraoperatively at C4-5 following bipolar stimulation (0.05 msec, 1 mA) of the dorsal columns 7 cm below the caudal recording electrode at T-1. *Lower Pair:* After the dorsal root entry zone lesions were made on the left side at C-8, the evoked potential amplitude was decreased on the left (C), but not on the right (D).

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old after removal of the stimulator. Prior to surgery there had been weakness and spasticity of the lower limbs, as well as sensory alterations along with bladder and bowel dysfunctions. The electrode plate and scar tissue were carefully removed, and there was no apparent change in the appearance of the spinal cord. Despite an improvement in the intraoperative evoked signal, after surgery the status of this patient worsened to paralysis. This is evidence that the intraoperative recordings taken from the dorsal surface of the cord are monitoring the condition primarily of the dorsal columns and not the status of the motor pathways, and may not predict the clinical outcome following surgery (see Discussion).

Discussion

Although the surface spinal cord potentials evoked by stimulation of dorsal roots and peripheral nerves have been studied in cats and in monkeys, it has been a problem to obtain adequate records of spinal cord activity in humans. Cord dorsum potentials have been recorded in humans, but these were not simultaneous multiple-point recordings on the exposed cord in adjacent root entry zones for localization purposes as are reported in this paper.

It has been important to be able to monitor spinal cord function in a non-invasive manner. However, non-invasive skin surface recordings provide extremely small potentials that are very attenuated. This is also the case with extraspinal recordings with electrodes in the interspinous ligaments. Epidural and even intrathecal recordings are still subject to the problem of orientation of the electrode with respect to the signal when the electrodes are placed without direct visual observation.

Cord dorsum potentials as well as nerve and spinal cord afferent activity have been recorded via skin surface leads after peripheral nerve stimulation. The leads were placed at separated intervertebral levels and records were made either in a bipolar mode between two leads or with a reference lead. In these records, both high and low frequency responses were somewhat attenuated and components of the responses were not well differentiated. The subjects were awake and reference leads were placed on muscle so that movement artifacts could have interfered with recordings. In spite of these problems, non-invasive surface recordings may be the only available or only practical method of assessing spinal cord function and could be useful for diagnostic purposes in which strict segmental localization is not the critical factor.

Postsynaptic cord dorsum responses were also obtained via needles placed into the interspinous ligament by Hahn, et al., and Lueders, et al. These potentials were somewhat larger in amplitude than those recorded from the skin surface, but it was not possible to discriminate various components, so the recordings could not be used for strict localization purposes.

Spinal cord potentials have been recorded from the epidural space in man by several groups, beginning with Shimoji and his associates. Although components were usually not well differentiated, these investigators used the recordings to analyze the effects of ketamine and morphine on the potentials and to study the interaction of pairs of evoked potentials.
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Results were compared with data obtained with animal experimentation. Caccia, et al.,6 using a technique similar to that used by Shimoji, et al.,43 observed functional differences in the evoked spinal cord response in disease states involving peripheral nerves and spinal cord although the potentials recorded were relatively small and not well differentiated. Jones, et al.,25 recorded spinal cord potentials after peripheral nerve stimulation from the epidural space in anesthetized patients who were undergoing surgery for scoliosis. Most recordings were made at upper thoracic levels.

Because it is important to be able to interpret these non-invasive and extradural recordings (which may be the only ones that are practical or even possible) reference to recordings made by placement of electrodes under direct visual observation should be helpful. Our recordings, although made to fulfill specific purposes of segmental localization and nerve root to spinal cord continuity, may serve this function because they were taken from the spinal cord surface under direct observation.

The evoked spinal cord dorsum potential recordings which we are reporting were performed in order to localize the major segmental input of particular peripheral nerves or dorsal roots. This was done so that therapeutic lesions could be made in the dorsal horn of the spinal segments of entry of nerves distributing only to an area of pain. The chronic-pain patients in whom these recordings were made had received a thorough sensory examination, with delineation of areas of analgesia and hypersensitivity, and the regions of dysesthesia and pain. Based on these observations the peripheral nerves and/or nerve roots that were involved could be predicted.

When the spinal cord was exposed at surgery for pain treatment, it was possible to visually position the electrodes directly on the cord surface. Especially in the lumbar enlargement, the dorsal roots are not clearly separated nor related at the root entry to a particular vertebral level. It is important to make electrical recordings after nerve stimulation to be able to pinpoint the exact dorsal horn area to be lesioned.

The cord dorsum response with electrodes placed at the root entry, at the segments of entry of stimulated peripheral nerves, provides an indication of the conduction capabilities up to the spinal cord. There is a principal spinal cord input of a segment or two for each peripheral nerve, so absolute localization can be obtained in this way (see Figs. 3 and 9). This is important in the case of herpes pain where the intact side can be used to provide localization as well as normal values of conduction velocity, amplitude, and form of the var-
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**FIG. 9. A comparison of root entry cord dorsum potentials recorded from the lumbar spinal cord in the cat and in man.** Left: The cord dorsum response to lateral paw stimulation (2.5 mA, 0.5 msec, 2 Hz) is shown in the cat, with the maximal response occurring at L-7. Right: Recordings from Case 11. The segmental localization of the maximal cord dorsum response to femoral nerve stimulation (20 mA, 0.5 msec, 3.3 Hz) at the L-1 root entry zone. Note the striking similarity between the cord dorsum potentials. PAS = primary afferent spike; N1a = presynaptic terminal potential; N1 = first postsynaptic negative wave; N2 = second postsynaptic negative wave; P = positive wave.

ious components for comparison with the diseased side. Certain parts of the cord dorsum response are generated in the dorsal horn, and can therefore provide some measure of the condition of the spinal gray matter at that level.

Our cord dorsum recordings were found to resemble those obtained in cat and monkey under similar conditions (Fig. 9). Experimental studies of the cord dorsum potential origins within the dorsal horn after cutaneous nerve stimulation in these species have shown that the negative waves reach a maximum peak in the middle layers (IV, V), and reverse to become positive in the ventral horn. Stimulation of muscle afferents also evoke cord dorsum potentials which at the lowest threshold are generated in the deeper layers of the dorsal horn. The postsynaptic negative wave is very small on the cord surface in response to low-threshold stimuli. Larger negative waves are recorded after high-threshold muscle afferent stimulation.

Sarnowski, et al., made recordings, from the skin surface over the spinal cord, of potentials evoked by peripheral nerve stimulation in cats. Both muscle and skin nerves were stimulated and comparisons were made in the evoked potentials recorded at various spinal levels. It was found that skin nerve stimulation produced a smaller afferent spike over the cauda equina and a larger negative postsynaptic response over the lumbar enlargement than did muscle nerve stimulation. Laminar and dural recordings over the thoracic cord were also made. As has been seen with similar recordings in humans there is an attenuation of amplitude and complexity of the signals at more superficial recording sites.

The cord dorsum potential recorded at the segmental root entry zone with a monopolar active lead after electrical stimulation of peripheral nerves consists of an initial triphasic spike (primary afferent spike) corresponding to primary afferent activity (presynaptic). The negative deflection (N1a) on the rising phase of the first negative slow wave, N1, is also presynaptic. It has been ascribed to activity in primary afferent terminals. The N1 wave is related to activity in cells in the dorsal portion of the dorsal horn (primarily laminae III and IV) after low-threshold afferent nerve activation, while subsequent waves are due to activation by smaller-diameter afferents and/or disynaptic activity. The deep and cutaneous afferents make different synaptic connections in the dorsal horn. Most of the N1 wave amplitude after stimulation at twice the threshold to a mixed peripheral nerve or dorsal root is due to activity in dorsal horn neurons after cutaneous nerve activation. Following the negative waves is a slow positive wave which has been related to primary afferent depolarization and is a sign of presynaptic inhibition. Several authors have reviewed the origins of the components of the cord dorsum response.

The study that we are reporting describes a methodology which approaches in accuracy that used in animal experimentation and which is technically reliable. Although applied during spinal cord surgery, our method does not add significantly to the risk involved in that neurosurgery. With stimulation of nerve roots and recording more proximally from the dorsal roots or from the dorsal columns, it is possible to measure the conduction capabilities of individual roots. These recordings can be accompanied by those from the cord dorsum after peripheral nerve stimulation to provide a more comprehensive monitor of the neural functional capacity.

There have been attempts to analyze the contribution...
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of the various cord sections to the evoked conducted response recorded over the dorsal surface of the spinal cord after peripheral nerve stimulation in the cat and monkey. By selectively placing spinal cord lesions, either the dorsal columns or both the dorsal columns and the dorsolateral fasciculus have been found to contribute to the evoked potential.

With peripheral nerve stimulation and cervical recording over the dorsal columns, the resultant response depends on two factors. The first is the strength of the stimulus. Stimulation of less than twice threshold activates only large-diameter afferent fibers, and conducted responses may be recorded in the dorsolateral column on that side. A stimulus two to four times the threshold level activates smaller-diameter fibers, and recordings of a conducted response in the dorsal column (and possibly the dorsolateral column) will be obtained. The mean conduction velocity for dorsal column fibers is about 30 m/sec, while it is about 50 m/sec in the dorsolateral column at the cervical level. The second factor determining the response is the position of the recording electrode. A medially placed electrode primarily records dorsal column potentials, and laterally placed electrodes may pick up dorsolateral fascicular activity. Although there is a synapse involved in lateral column conduction, the fibers in the dorsolateral column when activated from the periphery conduct more rapidly than dorsal column fibers. In the human, recordings taken from the surface of the spinal cord over the dorsal columns at a site several segments beyond the root entry of a stimulated peripheral nerve represent mainly the activity in the dorsal columns. Other afferent pathways are generally not monitored, and activity in descending fibers or the spinal gray elements are not recorded to any extent.

Although Macon and Poletti have reported an increase in conduction velocity at a cervical level after posterior tibial nerve stimulation, we have not found this to be the case (see Fig. 8). Experimental studies have shown that there is a progressive loss of dorsal column fibers to the dorsal horn along the spinal cord so that (in the cat) only 22% to 25% of the fibers entering the dorsal columns at a lumbar level are present in the fasciculus gracilis at the cervical level. With a single stimulus at one to two times the threshold level that activates the large-diameter fibers in the sciatic nerve from skin, joints, and muscle, the recorded dorsal column response becomes correspondingly smaller (Higgins, et al., unpublished data, 1981). Fibers drop out to supply Clarke’s column, and there is a progressive separation of the faster-conducted from the slower-conducted potentials so that, at an increasingly greater distance from the source of stimulation, the signal becomes more desynchronized and lower in amplitude. If a peripheral nerve of the leg is stimulated, and if entering the dorsal columns at a lumbosacral level are of A-alpha and beta size, most of the axons at the cat fasciculus gracilis at the C-3 segmental level are of A-delta size.

In one of our patients (Case 20), although afferent conducted responses (dorsal column evoked potentials) improved after surgery, the motor status did not improve but worsened instead. Levy and York have recently described a technique for intraoperative stimulating and monitoring motor tracts which may prove useful as an additional test of spinal cord integrity.

In the course of our study, both bipolar recordings with 1-cm inter-electrode distance and monopolar or referential recordings were made with the G2 or positive grid connected with a retractor. The stimulus artifact was more restricted with bipolar recordings. For this reason, bipolar recordings have often been made where the stimulus to recording distance is very short; that is, stimulation and recording of the dorsal columns. The problem associated with bipolar recording is that, as the waveform passes the initial recording lead to the second of opposite polarity, there may be interference or subtraction of the response amplitude if the distance between the bipolar recording electrodes is shorter than the conducted wavelength or the active area. Therefore, for purposes of localization of the root entry zone, monopolar recording was chosen to minimize subtraction and isolate the recording to the smallest area possible. In addition (again in contrast to results obtained by Macon and Poletti), we found that monopolar recordings generally produced higher signal amplitude which decreased the number of repetitions and therefore the recording time required. Finally, the largest body of comparative data, found in animal studies, has been recorded by a monopolar or referential system, and for purposes of correlation we used this method.

The recording techniques described in this paper allow accurate and effective localization of the DREZ for particular peripheral nerves. They allow monitoring of both peripheral and central evoked responses under normal and pathological conditions. This is important for interpretation and comparison in man and animals. The methods can also be utilized during surgical intervention for neuropathological conditions. The results can be correlated with pre- and postoperative neurological examinations for a more complete monitor of the neurological status of the patient. In some instances, the intraoperative evoked potentials do not predict possible deterioration of neurological function, and caution must be exercised in their interpretation.

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Avery (Avery Laboratories, Farmingdale, New York) fabricated the recording electrodes. Mrs. Flora Johnson was responsible for preparation of the manuscript.
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