The recent conversion of cervical cordotomy from an open procedure to a closed stereotaxic procedure has extended the benefits of cordotomy to many more patients. The four accepted steps of stereotaxic surgery must be followed: 1) definition of the radiologic coordinates of the target; 2) the use of a precision apparatus to approach the target; 3) physiological confirmation of the target; and 4) precise destruction of the target. Elimination of any one of these steps will increase the hazard to the patient.

The Target and its Environs

 Destruction of the lateral spinothalamic tract at the second cervical cord segment usually results in a contralateral loss of superficial pain, temperature, deep pain and viscer al pain below a level of C-3 or C-4 although overlap of the pain fibers from upper cervical levels with the ventral secondary ascending tract of cranial nerve V may preclude these high levels.6-8,15,16,19,20,22,23,39,40,46 The hazards of cordotomy at this level are due chiefly to the proximity of other important pathways as well as to considerable anatomic variation. Moreover, the second cervical cord segment is at the lower margin of the cervicomedullary junction where the anteroposterior diameter of the cord increases rapidly, and the position of tracts varies with the size and position of the motor decussation (Figs. 1-4).

A descending respiratory pathway (ventrolateral reticulospinal tract) is probably intermingled with and deep to the fibers of the anterior part of the lateral spinothalamic tract as concluded by Nathan.3,4,6,28 Recently, Hitchcock and Leece18 have presented evidence to show that automatic respiration in man is mediated through this reticulospinal pathway in the anterolateral quadrant of the cord (voluntary control of respiration is presumably through the corticospinal tract). Unilateral destruction of this pathway results in little functional respiratory loss unless the contralateral respiratory function is poor. In our experience as well as that of others, however, bilateral lesions involving the anterior portion of the lateral spinothalamic tract have been extremely dangerous in that the patients may be unable to respire while asleep. That this is not a new concern can be adduced from Foerster's letter of 1932 in which he stated "I personally would be afraid of a bilateral chordotomy at a high cervical level."

It may be possible to avoid these pathways where only bilateral sacral analgesia is required since the portion of the lateral spinothalamic tract from sacral levels is most posterior. However, should bilateral pain relief be required, one lesion is made at C-2 and the other lesion, 7 to 10 days later, by the anterior approach of Lin, et al., at C-5 or C-6, thus preserving diaphragmatic respiratory pathways on one side.25

The motor decussation usually extends from the obex to the C-1 level but the crossed corticospinal tracts may not assume their typical posterolateral position until they are at the lower portion of C-2 (Figs. 5-7). This decussation occurs over usually 8 to 10 mm; the arm fibers cross more superiorly than do the leg fibers. Contralateral leg weakness can occur either if the lesion is too high (toward C-1) or if there is variation and the decussation is as low as upper C-2. Not only may the location of the pyramidal tract and the number of fibers it contains vary, but also the relative number of decussating fibers. Barone2 stated that 80% of the
fibers of the pyramidal tract cross to one side while 20% do not; according to Nyberg-Hansen and Rinvik, the proportion of crossed fibers varies in man from 0 to 100%. Häggqvist found crossed and uncrossed fibers in both the lateral and ventral corticospinal tracts.

Aberrant corticospinal tracts have been described as well as a case in which the corticospinal tract did not decussate at all but remained in the anterolateral quadrant of the cord. There is also much variation in the size and the importance of the ventral corticospinal tract that usually carries motor fibers to the trunk and neck musculature. Encroachment on the lateral corticospinal tract, which is more medial and more anterior than we had suspected at this level, is to be avoided although destruction may produce surprisingly little permanent functional loss in terms of paresis of the extremity or bladder if the lesion is unilateral. As has been shown elsewhere with stereotaxic lesions in the thalamus, a unilateral error may be compensated but a bilateral symmetrical error is always dangerous.

The lateral spinothalamic tract is overlaid at this level by the ventral spinocerebellar tract which contains sacral, lumbar, thoracic, and cervical fibers in that order from posterior to anterior. This pattern is duplicated in the dorsal spinocerebellar tract which, however, carries fewer cervical fibers. A lesion eliminating all of the ventral spinocerebellar tract as well as the most anterior portion of the dorsal spinocerebellar tract produces ipsilateral ataxia of the arm.

The additional hazard of an undesirable neurological deficit produced by a lesion obliterating the anterior spinal artery must be considered. This is particularly important since Perese and Fracasso have pointed out that there were two such arteries in 13 of 28 human cervical spinal cords and that these arteries did not ordinarily follow the anterior median fissure.
Fig. 2. Cross section of the normal human spinal cord from the obex to C-2. The position of the lateral spinothalamic tract and the motor decussation is just above the C-1 nerve root. Weil stain.

Fig. 3. Cross section of the normal human spinal cord from the obex to C-2. The position of the lateral spinothalamic tract and the motor decussation is at the level of C-1 nerve root. Weil stain.
Fig. 4. Cross section of the normal human spinal cord from the obex to C-2. The position of the lateral spinothalamic tract and the motor decussation is at the level of C-2. Weil stain.
Radiologic Coordinates

We have used the technique of Mullan\textsuperscript{26,27} as modified by Rosomoff\textsuperscript{25} for high cervical cordotomy and that of Lin, \textit{et al.}\textsuperscript{28} for anterior cervical cordotomy. Innovar (McNeil Laboratories) premedication and local anesthesia were used. The anterior cord border was delineated by air. The midline on the anterior posterior view (as determined by bisection of the interpediculare distance or odontoid) was used to approximate the midline of the cord; the lateral margin of the odontoid process corresponds usually to the lateral margin of the dura at this level.

Before puncturing the dura, care was taken to direct the No. 18 gauge needle inferiorly toward the lower part of the C-2 segment and well anteriorly to avoid the motor pathway. Radiologic guidance of the electrode insertion in two planes was obtained by the use of C-arm fluoroscopy utilizing image intensification. No x-rays were made but the image was taped for instantaneous TV replay. The electrode tip was positioned 2 mm posterior to the anterior border of the cord and 2 mm from the midline.

If the pain problem was severe enough to require bilateral cordotomy, particularly

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Fig. 5. Parasagittal section of normal human spinal cord from medial to lateral. The O point on the millimeter scale is at the C-2 nerve root and the anterior border of the cord at C-2. \textit{Inset}: Diagram shows the plain of the section at the level of C-2. This section illustrates the relationship of the lateral spinothalamic tract at C-2 to the decussating motor pathways. Weil stain.

Fig. 6. Parasagittal section of normal human spinal cord from medial to lateral. The O point on the millimeter scale is at the C-2 nerve root and the anterior border of the cord at C-2. \textit{Inset}: Diagram shows the plain of the section at the level of C-2. This section illustrates the relationship of the lateral spinothalamic tract at C-2 to the decussating motor pathways. Weil stain.
when lumbosacral in origin, an attempt was made to position the electrode more posteriorly into the sacral region of the lateral spinothalamic tract, sparing the more anteriorly situated respiratory fibers. Ideally, in contralateral sacral pain the electrode position should be 4 mm from the anterior margin of the cord and 4 mm from the midline. In our experience, however, making a lesion purely on the basis of radiologic coordinates has been unsatisfactory and hazardous not only because of anatomic variation but also because the pia is tough and the cord mobile. We have demonstrated at open operation that the sharpened electrode tip may displace the cord 5 mm in any direction (in spite of dentate attachments) without penetrating the pia. Thus, the electrode tip in the final position is usually 0 to 5 mm across the midline on the x-ray.

Figures 8 and 9 illustrate a case in which the position of the electrode as shown radiologically was correlated with the position of the lesion in the spinal cord at autopsy. This patient suffered from chronic intractable pain in the left leg due to nonunion of a fractured femur. An attempt to relieve this pain by stereotaxic cordotomy with a single lesion in October, 1966, produced no relief of pain or analgesia; however, a Babinski and a very minimal weakness of the right arm was noted. A second attempt at stereotaxic cordotomy in March, 1967, resulted in left-sided analgesia to the level of C-3 and relief of pain with a single lesion. The patient died 6 months later from another cause.

**Physiological Corroboration**

The comparatively small size of the target, its irregular shape, anatomical variation, the important pathways that surround it in the cord, and the relative imprecision of radiological methods, especially in view of the mobility of the cord and the toughness of the pia, all demand confirmation that the electrode is in the spinothalamic pathway before a lesion is made. At present this corroboration is obtained in three ways: by measurement of impedance, electrical stimulation, and incremental enlargement of the lesion with concomitant clinical testing.
Stereotaxic Cervical Cordotomy

**Fig. 8.** Polaroid x-rays made during the second cordotomy. *Left:* The tip of the electrode is well across the midline. *Right:* The tip of the electrode is about 2 mm posterior to the anterior cord, which is outlined by air.

**Impedance Measurement.** Different parts of the central nervous system have different compositions and thus physical properties; some tracts are heavily myelinated while cells are not myelinated at all. The spinal cord and its environs (cerebrospinal fluid) may each be considered as being composed of various resistances and capacitances which do offer different opposition to the flow of alternating current injected between the electrode tip and an indifferent electrode which is a 20 gauge, 1⅛ inch hypodermic needle inserted into the contralateral deltoid muscle. The measured impedance (Fig. 10) is determined by the alternating voltage divided by the alternating current and is expressed by

**Fig. 9.** Cross sections of the cord at C-2 in the same patient as in Fig. 8. *Left:* Note lesion in the anterolateral quadrant corresponding to the second cordotomy in the Fig. 8 x-rays. The scarring posterior to the dentate ligament on the same side represents the first cordotomy. *Right:* Lower cervical section shows degeneration in the corticospinal pathway caudal to the lesion. Weil stain.
magnitude (ohms) and by the angle ($\theta$) between the phases of voltage and current. The measurement of impedance and its changes has enabled us to know whether the tip of the electrode is in cerebrospinal fluid (CSF), merely in contact with the cord and penetrating, or in the cord.

To establish the range of values at these sites, a barbiturate-anesthetized cat was operated on so as to expose the upper cervical cord. Using the electrodes commercially available (Codman and Shurtleff, Inc., Trocar pointed, Teflon insulated electrode wires, 3 mm long tip) for the human stereotaxic cordotomy and an impedance meter (Hewlett-Packard Model 4800) linked with an X-Y recorder (Mosley Model 7001 AR), we measured the impedance (Table 1, cat) between an indifferent electrode imbedded in cervical muscle and the recording 3 mm tip as it was positioned under direct vision initially in CSF, indenting the surface of the cord, then fully into the dorsal column of one side of the cord. This procedure was repeated in four different cord positions; the results showed good agreement in the impedance measurements (Tables 1 and 2, cat).

The opportunity was taken in two patients where open cordotomies were performed to visualize the position of the electrode tip and compare it with the recordings of impedance obtained (Table 1, open cordotomy). It became obvious that there was a distinct increase in the impedance as the electrode tip made contact with the pia of the cord (Tables 1 and 2). Due to the “toughness” of the pia and mobility of the cervical cord it was difficult to imbed the sharp tip; when this

| TABLE 1 |

**Impedance measurements in four different cord positions showing step-like relationship of increase in impedance with electrode advancement from CSF into cord**

<table>
<thead>
<tr>
<th>Site</th>
<th>Cat Experiment</th>
<th>Open Cordotomy</th>
<th>Stereotaxic Cord</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Z$</td>
<td>$\theta$</td>
<td>$Z$</td>
</tr>
<tr>
<td>(1) CSF</td>
<td>180</td>
<td>57</td>
<td>247</td>
</tr>
<tr>
<td>(2) Cord Contact</td>
<td>280</td>
<td>29</td>
<td>370</td>
</tr>
<tr>
<td>(3) In Cord</td>
<td>468</td>
<td>29</td>
<td>410</td>
</tr>
<tr>
<td>(4) After Lesion</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>A = Difference (2)−(1)</td>
<td>100</td>
<td>—</td>
<td>115</td>
</tr>
<tr>
<td>B = Difference (3)−(2)</td>
<td>188</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>A + B</td>
<td>288</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
TABLE 2

Impedance measurements showing step-like relationship of impedance to electrode advancement

<table>
<thead>
<tr>
<th>Case</th>
<th>C.S.F.</th>
<th>Contact Cord</th>
<th>In Cord</th>
<th>After Lesion</th>
<th>No. of Insertions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Z  θ</td>
<td>Z  θ</td>
<td>Z  θ</td>
<td>Z  θ</td>
<td></td>
</tr>
<tr>
<td>Cat open cord</td>
<td>180 57</td>
<td>280 29</td>
<td>468 29</td>
<td>350 3</td>
<td>4</td>
</tr>
<tr>
<td>P.J. open cord</td>
<td>168 30</td>
<td>300 90</td>
<td>410 90</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>H.H. open cord</td>
<td>325 64</td>
<td>440 59</td>
<td>—</td>
<td>—</td>
<td>*</td>
</tr>
<tr>
<td>P.B. s.c.</td>
<td>148 48</td>
<td>300 38</td>
<td>458 55</td>
<td>—</td>
<td>4</td>
</tr>
<tr>
<td>J.L.H. s.c.</td>
<td>175 48</td>
<td>—</td>
<td>422 30</td>
<td>1000 43</td>
<td>8</td>
</tr>
<tr>
<td>G.F. s.c.</td>
<td>191 11</td>
<td>300 7</td>
<td>680 6</td>
<td>900 8</td>
<td>3</td>
</tr>
<tr>
<td>B.V. s.c.</td>
<td>151 42</td>
<td>239 40</td>
<td>520 20</td>
<td>—</td>
<td>4</td>
</tr>
<tr>
<td>J.J. s.c.</td>
<td>200 28</td>
<td>310 42</td>
<td>350 43</td>
<td>375 25</td>
<td>3</td>
</tr>
<tr>
<td>E.C. s.c.</td>
<td>288 44</td>
<td>366 60</td>
<td>463 65</td>
<td>600 55</td>
<td>4</td>
</tr>
</tbody>
</table>

* No insertions were made in this patient.

s.c. indicates stereotaxic cordotomy.

was achieved, however, there was another step-like increase in the impedance (Table 2, Fig. 11). The increases in impedance with the insertion of the electrode tip from CSF to cord contact and then into it, allows us to interpret the relationship of the electrode tip to the cord in the non-visualized stereotaxic cordotomy (Table 1, SC; Fig. 11).

CSF impedance measurements in the stereotaxic cordotomies are known since the fluid is coming out of the spinal needle as the electrode is threaded down; the value recorded at first contact with the fluid remains constant (average, 190 ohms) until the electrode tip is radiographically at the lateral border of the odontoid on the anteroposterior view (which usually indicates the lateral border of the cord). At this location the impedance suddenly increases by about 100 ohms to a stable reading of 290 ohms, presumably because of electrode contact with the pia. As the electrode is advanced the impedance gradually increases, by an average of 310 ohms, to a stable reading of 600 ohms (range 350 to 750 ohms, Fig. 11). Tables 1 and 2 are compiled from the first

![Fig. 11. Resistivity values derived from increases in impedance. Circle = cat; triangle = open cordotomy (Op) in two patients; square = stereotaxic cordotomy (S) in 20 patients.](image-url)
six stereotaxic cordotomies performed, however, Fig. 11 (S) is a composite of measurements from 20 patients. When the stable mean reading of 600 ohms is reached, radiological examination shows the electrode tip to be at or across the midline of the spinal canal by 0 to 5 mm.

The radiofrequency (rf) lesion equipment (Radionics Model #RFG-2A) is set to produce a current of 280 mA in the “Test” position. If the electrode is so positioned into the cord as to give an impedance in the high range (about 600 ohms) then the rf current when in “Operate” to produce a lesion will usually read about 50 mA. However, if the radiological position indicates that the electrode should be in the cord and impedance measurement is not in the high range but is in the intermediate range of 300 ohms, the radiofrequency current when operated usually reads 100 to 150 mA, and usually little or no clinical results are achieved.

Following the rf lesion, the impedance was recorded in four cases and found to be markedly increased by $1\frac{1}{2}$ times the previous level (Tables 1 and 2). This indicates a conversion of tissue to more resistant material or the formation of gas bubbles. A tissue coating of the electrode sometimes occurs that alters the impedance which is then markedly higher than before. Occasionally after a lesion has been made, it is necessary to clean the electrode tip before reinsertion.

It is important to convert the measurements of impedance to the standard readings for resistivity (ohm-cm). It is known that the resistivity of cerebrospinal fluid and that of normal saline (0.9%) are similar (60 ohm-cm). Four electrodes were selected, three of them coming from a batch of 50 standard electrodes which had 3 mm tips exposed. The fourth one had the 3 mm tip cut back to expose 5 mm. These four electrodes were then inserted into a large beaker which contained 200 ml of normal saline. An indifferent electrode was placed at the opposite side of the beaker. Impedance was recorded between the indifferent electrode and each of the four electrodes, the frequency of testing was altered from 5000 cycles/sec to 50,000 cycles/sec ($H_Z$). Following this, 100 ml of distilled water was mixed thoroughly with the saline. Further readings were then taken from each of the electrodes. This procedure of dilution and recording was continued until 1200 ml was the total volume.

A comparison of the results obtained using the two frequencies (5000 $H_Z$ and 50,000 $H_Z$) showed little or no difference. Since the 50,000 $H_Z$ frequency was used for measuring the impedance in stereotaxic cordotomies, the measurements from the four electrodes following dilution of 0.9% saline were plotted using this high frequency (Fig. 12). At the 200 ml mark (0.9% saline) on the graph 60 ohm-cm was inserted. With each 100 ml added, the resistivity was increased by 30 ohm-cm because the original 200 ml of saline (0.9%) was diluted. In Fig. 12, the 5 mm tip electrode shows a smaller impedance reading as compared to the 3 mm tip electrode. There is a uniformity of results obtained with three 3 mm tip electrodes. It can then be stated that the average impedance of the anterolateral part of the spinal cord (mainly myelinated fibers) recorded in this manner using the standard cordotomy 3 mm tipped electrode is in the order of 280 ohm-cm (600 ohms, Fig. 11).

Our results are in agreement with those of Ranck and BeMent who measured the specific impedance in the transverse direction of the dorsal columns of the spinal cord in cat and then again measured it in the longitudinal direction. Ranck and BeMent's results show that the impedance in the transverse direction of the dorsal column is in the order of 664-1200 ohm-cm and the specific impedance in the longitudinal direction is in the order of 138-212 ohm-cm. Our measurement of impedance of the anterolateral column is a result of measuring transverse and longitudinal impedance. The results when the electrode tip is presumably in the cord has a range from about 160 to 340 ohm-cm. The large variation is not due to the variation in electrode tip size as the standard electrodes were used. However, it could be due to the fact that the electrode tip may be in deep enough to touch the motoneuron pool (grey matter), and more probably that the proximal part of the exposed tip may not be fully in the anterolateral column and as a result would be in contact with cerebrospinal fluid and so lower the resultant reading of impedance. In taking the result as a whole, however, it still lies within the two ranges of
readings taken by Ranck and BeMent for the dorsal columns of cat. Freygang and Landau\textsuperscript{14} reported the specific impedance of cat subcortical white matter to be about 1.5 times that of the cortex or 333 ohm-cm. It is therefore important to provide a conversion graph so that the electrodes that one uses for impedance measurements can be calibrated into resistivity and the results used to compare with those from other investigators using other types of electrodes in other situations.

**Electrical Stimulation.** Presuming from the impedance measurements that the electrode is in the spinal cord, we then undertook monofocal stimulation to further localize the tip as has been previously reported by Mullan\textsuperscript{26} and Sweet, \textit{et al.}\textsuperscript{44} A stimulator (Grass Model S4) was connected so that the anode is an indifferent electrode in the contralateral deltoid muscle and the cathode is the cordotomy electrode. At a frequency of 1–6 cycles per sec the stimulus (0.3–1.5 V/1 msec duration) elicited ipsilateral motor responses in the trapezius muscle (Table 3). The lower threshold of stimulation necessary to elicit twitching of this muscle the closer the electrode tip is to the anterior part of the cord (ventral root fibers and motoneurons of C-2). Conversely, the higher the voltage required the farther posterior and lateral to the motoneurons the electrode tip is.

Should synchronous movements of the fingers, deltoid, or the lower extremity on the same side be obtained it suggests that the electrode is in or close to the more posterior and laterally placed descending motor fibers (cortico- and rubrospinal tracts). The threshold for evoking a response from these distant muscle groups is at least 0.8 V and up to 1.5–2.0 V/1 msec duration (Table 3).

At the higher frequency range of 50–60 cycles and with sometimes double the voltage required for evoking motoneuron responses (0.4 V–4.0 V/1 msec duration), it is possible to elicit sensory responses, described by the patients as “tingling” on the contralateral side of the body. The electrode tip is then presumed to be in or close to the lateral spinothalamic tract. Table 3 is a composite of data from 24 cases which were stimulated in the anterolateral cord; of the 19 patients who had the higher frequency of stimulation (50–60 Hz) applied, 17 experienced “tingling” in either the contralateral upper or lower half of the body depending upon the anterior or posterior positioning of the electrode in the anterolateral part of the cord.

The trapezius motoneurons were found also at C-3 cord level as was shown when

![Fig. 12](image-url) Fig. 12. The graph shows the conversion of impedance (ohms) recorded by three similar electrodes (3 mm long tips) and another similar electrode which has a 5 mm long tip into resistivity (ohm-cm). This was achieved by starting with 200 ml of 0.9% sodium chloride solution and diluting up to 1200 ml.
TABLE 3
Results of stimulation of anterolateral cord during stereotaxic
cordotomy at the C-2 level in 24 patients

<table>
<thead>
<tr>
<th>Area Stimulated</th>
<th>Result</th>
<th>No. of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle</td>
<td>ipsilateral trapezius contraction (0.3-1.2 V/1 ms/2-6 Hz)</td>
<td>23</td>
</tr>
<tr>
<td>Corticospinal tract</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-6 level</td>
<td>ipsilateral contraction index finger (1 V/1 ms/3 Hz)</td>
<td>1</td>
</tr>
<tr>
<td>C4-5 level</td>
<td>ipsilateral contraction deltoid (0.6-1.0 V/1 ms/6 Hz)</td>
<td>2</td>
</tr>
<tr>
<td>Lateral spinothalamic tract</td>
<td>contralateral tingling (0.4-4.0 V/1 ms/50-60 Hz)</td>
<td>17 of 19</td>
</tr>
<tr>
<td>anterior part</td>
<td>upper extremity</td>
<td></td>
</tr>
<tr>
<td>posterior part</td>
<td>lower extremity</td>
<td></td>
</tr>
<tr>
<td>Anterolateral cord (region?)</td>
<td>nausea (1 V/ 1 ms/3 Hz)</td>
<td>1</td>
</tr>
<tr>
<td>(region ?)</td>
<td>abdominal burning (0.4-0.8 V/1 ms/60 Hz)</td>
<td>2</td>
</tr>
</tbody>
</table>

The electrode was inserted at this level in one of the open cordotomies. Respiratory jerking was elicited also in this patient at the C-3 level (0.8 V/1 msec/4-6 cycles).

**Correlation of Analgesia with the Lesion.** Correlation of the areas of analgesia obtained as the lesion is made with the estimated position of the electrode corroborates the presence of two clinically useful patterns within the lateral spinothalamic tract: a dermatomal pattern, in which the cervical fibers are more anteromedial, the sacral fibers most posterolateral, and the thoracic and lumbar fibers interposed and a pattern for modality in which superficial pain, temperature, deep pain, and visceral pain are disposed from without to within (Fig. 13).

In 1926, Peet reported: “It is the depth of the incision, particularly in the anterior portion of the anterolateral tract, which determines how closely the level of analgesia approaches the level of sensory distribution of the segment operated upon. The highest level of lost pain and temperature sensation was obtained when the incision of the cord extended directly forward through the anterior root.” In 1937 we reached the conclusion that, in order to obtain high levels of analgesia which would persist, the incision should be carried not just to or through the anterior nerve root, but to a point from 1 to 2 mm. anterior to it. This belief was later confirmed by Hyndman and Van Epps and by Weaver and Walker in the monkey. Hyndman and Van Epps demonstrated that it was possible to produce analgesia over the chest and abdomen without including the legs in the sensory change. It was their opinion at the time (based on six cases) that the region that extends 2 mm anterior to the dentate ligament contains no fibers conducting sensations of pain and temperature. Although there is undoubtedly some anatomical variation among individuals, four cases which Kahn and Rand have reported disprove this conclusion. Walker had concluded that sacral fibers “may be spared in dorsal or cervical anterolateral cordotomy in which the incision is made 1 to 2 mm anterior to the dentate ligament.” (Yoss has shown, in the monkey, that a lesion in the most dorsolateral portion of the lateral spinothalamic tract prevents painful stimuli applied to the exposed contralateral Achilles tendon from reaching consciousness.)

While it is certainly true that visceral pain
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is deep and probably bilateral, only a few cases had suggested that temperature is deep to superficial pain\textsuperscript{42,43} and there was even less evidence for the position of deep pain.\textsuperscript{49,50} The accepted concepts of overlap may not be entirely correct since it appears that overlap is not uniform;\textsuperscript{10–12} there is more specificity to pinprick at hand and foot levels than at trunk where more overlap as well as poorer nerve endings exist. Temperature sense is more specific than pain sensation since it appears later phylogenetically; this results in levels to hot or cold that may be one-half segment higher than levels of analgesia after cordotomy.\textsuperscript{8,24} There is also much less specificity for visceral sensation.

In those cases where it is necessary to increase the size of the lesion by moving the electrode posterolaterally from its initial anteromedial position it is possible to record the progressive spread of the sensory loss in the contralateral upper extremity over the trunk, lower extremity, and finally sacrum when the electrode is most posterolateral. We have also noted that, as the lesion progresses from deep within the lateral spinothalamic tract more superficially, contralateral deep pain is lost first followed by temperature and then superficial pain. The converse is true as well. Evidence from cases of syringomyelia also support this pattern. It is therefore mandatory to test both upper and lower extremities not only for pinprick but for the other modalities as well before increasing the lesion.

Radiologic techniques guide the electrode to the anterolateral quadrant, impedance measurements can assure its penetration into cord, and the techniques of stimulation permit estimation of its position within the anterolateral quadrant. Our experience with these techniques is similar to that being obtained by Nulsen, et al.\textsuperscript{29} Each of these methods is necessary since each gives differ-

![Figure 13](image-url)

**Fig. 13.** Cross section of human spinal cord at the second cervical level. Note the dermatomal pattern across the lateral spinothalamic tract as shown on the right side of the diagram and the pattern for modality across the lateral spinothalamic tract on the left side of the diagram. Note also the ventrolateral reticulospinal tract which is probably the descending pathway for automatic respiration intermingled with the fibers of the lateral spinothalamic tract.
ent degrees of accuracy. The finest degrees of accuracy will probably result from a recording of spontaneous and evoked potentials from the cord. At the very least, however, a microelectrode will be required to record cell and tract activity. The reduced size of the electrode tip will introduce new technical problems, and the low signal strengths may require computer averaging techniques to separate them from the background "noise."

**The Lesion**

As in any stereotaxic procedure it is necessary to know and to be able to control the volume and the shape of the lesion as well as the position in which it is made. At present we produce ellipsoidal lesions from 4 to 5 mm in length and 2 to 3 mm in diameter using a radiofrequency generator that is set to deliver 70 to 80 mAmp of current to the electrode in increments of 15 to 20 sec. We have experimented with various types of electrodes, and the most satisfactory for our present capabilities appears to be the sharpened stainless steel silicone-sheathed electrode with 3 mm of exposed tip beyond the Teflon sheathing and the entire electrode protruding 4 mm beyond the tip of the No. 18 gauge thin-wall needle described by Rosomoff. In our experience, it is unusual for the Teflon-sheathed portion of the electrode to penetrate the cord. It has been our practice to increase the lesion size and position by varying the position of the electrode within the anterolateral quadrant of the cord. With the introduction of our present techniques, we have been able to reduce the number of lesions to an average of 3 per patient (20 patients). Clinical testing of the analgesic levels as the lesion is made affords further confirmation of the electrode position. Maximum lesion size occurs usually in about 15 to 20 sec and is indicated by a decrease in rf current.

Approximately 100 patients have been treated. Stereotaxic cordotomy in no way changes our already stated criteria of selection of candidates for open cordotomy but has greatly reduced our contraindications to the procedure. Previously we were loathe to perform the open procedure on any patient with a short life expectancy for the simple reason that often these patients were poor surgical risks and the added burden of convalescence was too onerous. It is in this area that the benefits of cordotomy have been extended to many more patients. By far the largest share of our cordotomies (80%) are still done to relieve pain of malignant disease. There were two deaths early in the course of our series; in both of these patients respiratory failure occurred as a result of a bilateral high cervical procedure. Most of the patients complain of ipsilateral head and neck pain for several days following the procedure and, in 25% this is a bitter complaint. In approximately 20% of the cases we have been unable to obtain a satisfactory level of analgesia, or the patients have not been satisfied in spite of a good technical result. The same complications exist with the stereotaxic procedure as with the open procedure, but at a lower rate.

It is interesting that in almost a third of our cases in which we thought a unilateral cordotomy would suffice the immediate and persistent appearance of pain on the opposite side eventually required another cordotomy. Although it is difficult to believe that this pain was present and unrecognized or dwarfed by the original pain, one can only speculate as to the mechanism of its appearance. It is worth noting again that the results of cordotomy in nonmalignant cases (if these are carefully selected) are much better than the results in malignancy where the patient is beset with all of the other manifestations of his disease, particularly the patient's mental reaction to the knowledge that he has a malignancy. The best results are still obtained with unilateral cordotomy and the complications are less. It is hoped that, as more accurate techniques of localization are developed and applied, the bilateral cordotomy will become less formidable. As our experience with this stereotaxic cordotomy has increased, our results have improved. Since we have added the additional physiological dimension, we have noted no serious complications and the results are better.

**Summary and Conclusions**

Stereotaxic cordotomy is evolving as a better procedure than open cordotomy not because it is easier but because complications can be lessened and its benefits extended to sicker patients. However, since
this is essentially a blind procedure, it is necessary to replace the visual localization of the lesion site by neuroradiologic and electrophysiologic techniques. The target, the lateral spinothalamatic tract, is selected on the basis of our knowledge of anatomy. The approach to the target is guided radiologically; impedance gives us assurance that the electrode is in the spinal cord; stimulation points out the position of the electrode in the anterolateral quadrant of the cord; and a staged lesion coupled with clinical testing acts as further target corroboration. These techniques are somewhat analogous to the use of the various objectives of a microscope in centering on the target.

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