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**Abstract**
Epidural spinal cord stimulation (SCS) has gained a secure place in the armamentarium of the surgeon treating chronic pain conditions (1, 2). The complexity of the intraspinal structures and their different susceptibility to electrical signals, however, has made it difficult to characterize the effects of the stimulation. Some important recent work has helped shed light on the electrical properties of the intraspinal structures and on the electrical field potentials generated with epidural spinal cord stimulation. This work, initially pioneered by Sin and Coburn, has successfully been expanded and perfected by Holzheimer and Struijk at the University of Twente, The Netherlands (3–8). The Dutch scientists developed a computerized volume conductor model of the spinal cord to represent in extreme detail the electrical properties of all the intraspinal structures, including the dorsal column and dorsal root fibers. The model can simulate the effects of epidural stimulation with different electrode geometries and configurations (8). The data generated from the model were then validated by comparing them to a large number of data collected by the author in implanted subjects (9–12). The author also conducted a detailed analysis of the clinical properties of the activation of the intraspinal structures at various electrode positions in the spine (13, 14).

**Key Words:** spinal cord stimulation, pain, neuromodulation, dorsal columns

**Anatomical and Electrical Properties of the Intraspinal Structures**

Anatomy of the Large Myelinated Afferent System

**Dorsal Roots**
The majority of dorsal root fibers, upon entering the spinal cord, proceed toward the dorsal columns where they bifurcate into an ascending and a descending branch (15, 16). In comparison with longitudinal dorsal column fibers, dorsal root fibers have a curved shape and they differ in orientation with respect to the spinal cord and the implanted electrodes. Dorsal root fibers average 15 μm in diameter. Proximal to the dorsal ganglion, the dorsal root fibers fan out in an ascending dorso medial direction to form the rootlets that enter the spinal cord at different angles. Struijk and Holzheimer have studied the effect of the curvature of the dorsal roots on their electrical threshold (5, 6). According to their model, since the root filaments are immersed in the well conducting cerebrospinal fluid and then enter the spinal cord, which has a lower conductivity, the lowest threshold is at the level where the dorsal root fibers enter the dorsal horn (dorsal root...
entry zone). They also found that the angle of the fibers as they enter the spinal cord has a significant effect on their threshold. The excitation threshold increases with increasing the angle between the nerve fiber and the transverse plane. The curvature of the rootlet also affects the excitation threshold: If the fiber is bent away from the cathode, the excitation threshold will decrease, whereas an opposite curvature will increase it.

**Dorsal Columns**

The dorsal columns are formed mostly by collaterals of large diameters fibers that mediate tactile sense and limb proprioception. Besides entering the dorsal columns, these fibers also give off collaterals that enter the dorsal horn from its medial aspect and terminate in the deeper laminae of the gray matter (17).

The distance over which a given ascending primary afferent fiber travels in the dorsal column depends upon its peripheral receptor type. Three systems of primary afferent fibers have been described: a short system, an intermediate system, and a long system (18, 19). The short system terminates within one or two segments and includes mostly small myelinated and unmyelinated fibers. The intermediate system projects rostrally 4 to 12 segments and includes mostly large myelinated fibers. The long system projects all the way to the medulla and the fibers synapse in the dorsal column nuclei. Most of the axons are large myelinated fibers. The conduction velocities of the axons in the intermediate and long system slow near the point of entry of the axons in the spinal cord from the dorsal roots, suggesting that the fibers become narrower as collaterals are given off at this level. The long system axons slow again near the level of the cervical enlargement, suggesting that collaterals are given off at this level as well (18). The long system of primary afferent fibers in the dorsal columns, which continue rostrally to the medulla where they synapse with the dorsal column nuclei, carries tactile sensation and proprioception. The short and intermediate systems serve other purposes, such as providing information to neurons at segmental levels and to such pathways as the dorsal spinocerebellar tract (19).

The lemniscal fibers enter the lateral part of the dorsal columns and gradually shift medially and dorsally. Fibers entering at higher segmental levels join lower level fibers laterally. About 85% of the dorsal column fibers are primary afferents. All afferent fibers in the dorsal columns issue collateral branches into the gray matter where they freely arborize. These collaterals only occur at the nodes of Ranvier of the ascending or descending main fibers. It has been estimated that the nodal membrane of a branching fiber is up to 50% larger than the area of a nonbranching node. The presence of collateral influences the transmembrane potentials at the node (18).

The diameter of the dorsal column fibers diminishes as they extend rostrally, averaging 12 microns at their origin and decreasing to about 8 microns a few segments more rostrally. In addition to the primary afferent fibers projections, the dorsal columns contain the axons of cells located in the dorsal horn. These axons form the postsynaptic dorsal column pathways, and the cells of origin are located in lamina III-V of the dorsal horn.

**Electrical Properties of the Intraspinal Structures**

**Conductivity of Individual Structures**

The intraspinal structures can be equated to a non-homogeneous conductor. The most relevant structures are the dorsal epidural space, which mainly contains fat, the dura mater, the cerebrospinal fluid (CSF), the nerve roots, and the spinal cord. The CSF has the highest conductivity, as measured in samples from human subjects by Struijk and coworkers (6). The conductivity of the dura mater is unknown. The conductivity of the bone, white matter, gray matter, and epidural fat were studied by Geddes and Baker (20). The white matter fibers have the highest conductivity after the CSF. Transversely orientcd white matter fibers have a much lower conductivity than longitudinal fibers. The conductivity of the epidural space structures and of the vertebral bone is negligible. In their computer model, Struijk and colleagues calculated the conductivity of the dura mater to be similar to that of the epidural space structures (6). (See Table 1.)

As a result of these parameters, 80% to 90% of the current flowing between electrical contacts actually flows through the CSF. This means that the single most important factor determining the current distribution in epidural SCS is the width of the CSF space between the electrode and the neural struc-
Table 1. Conductivity of Intraspinal Structures

<table>
<thead>
<tr>
<th>Structures</th>
<th>Conductivity (1/Ωm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grey Matter</td>
<td>0.23</td>
</tr>
<tr>
<td>White Matter</td>
<td></td>
</tr>
<tr>
<td>Longitudinal Fibers</td>
<td>0.60</td>
</tr>
<tr>
<td>Transverse Fibers</td>
<td>0.083</td>
</tr>
<tr>
<td>CSF</td>
<td>1.7</td>
</tr>
<tr>
<td>Epidural Space</td>
<td>0.04</td>
</tr>
<tr>
<td>Dura Mater</td>
<td>0.03</td>
</tr>
<tr>
<td>Vertebral Bone</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Features. The width of the CSF space varies according to the spine level. It is related to the dimensions of the bony canal as well as the dimensions of the spinal cord. The average dimensions of the spinal cord vary at different levels, as reported by Fix (21). At the midcervical level, the average transverse diameter is 7.6 mm; at the midthoracic level, 7.2 mm; and at the low thoracic level, 7.8 mm. The width of the dorsal subarachnoid space was studied by Holsheimer and associates in patients undergoing MRI scans (22). The mean width of the dorsal CSF layer was 2.5 mm in the midsacral, 5.8 mm in the midthoracic, and 3.6 mm in the low thoracic spine.

Factors Affecting the Excitation Threshold of Dorsal Columns and Dorsal Root Fibers (Fig. 1)

Fibers Diameter. There is a linear relationship between fibers diameter and conduction velocity. While dorsal root fibers can be compared to simple straight nerve fibers, dorsal column fibers have a more complex structure, since they issue collaterals perpendicular to the main fibers that run into the gray matter. Dorsal root fibers have a diameter that is at least double that of a dorsal column fiber. Large myelinated fibers in the dorsal roots average 10 μm to 20 μm (16).

Fibers Curvature. Curvature of the fibers affects their excitation threshold. According to the modeling studies by Struijk and coworkers, a curvature away from the cathode will decrease the excitation threshold, whereas an opposite curvature will increase it (5). The angle of entry of the dorsal rootlets into the spinal cord also influences their excitability. Generally, a decreasing angle between the spinal cord and rootlets results in an increasing threshold.

Collateral Branching. Collateral branching of the dorsal column fibers also carries a significant effect on the fibers’ excitability. Struijk and coworkers demonstrated that the threshold stimulus for excitation and blocking at branching nodes is decreased up to 50% as compared to nonbranching node (4). This is particularly true at larger electrode–fiber distance, which is the common situation in epidural SCS. At a small electrode–spinal cord distance, the effect of branching is minimal. As the distance increases, fibers with collaterals will exhibit a progressively lower excitation threshold. This was confirmed by Racan in a review of experimental studies collected from various authors (23).

While dorsal column fibers have mostly a longitudinal arrangement, dorsal root fibers have a curved shape and they differ in orientation with respect to the spinal cord and the implanted electrodes. Dorsal root fibers have a threshold stimulus that is less than half that of dorsal column fibers. The difference in the threshold is due to three factors: (1) the different fiber orientation with respect to the electrode, (2) dorsal root fibers are curved while dorsal columns fibers are straight, and (3) dorsal root fibers travel across the interface between a low-conductivity (spinal cord) and a high-conductivity (CSF) compartment. Dorsal root fibers in the low thoracic area have a relatively higher threshold with respect to dorsal root fibers in the midthoracic area. This is due to the more acute angle that low thoracic fibers have upon entering the spinal cord. Even though dorsal root fibers usually have a lower threshold, in the case of a small CSF width the dorsomedial dorsal column fibers might be stimulated first (8). This
data correlate well with the clinical experience that paresthesias are initially felt at the segmentary level. Occasionally, especially in the cervical area, a perfectly midline electrode, instead, will elicit paresthesias in distal areas such as the feet.

**Clinical Correlations**

In a collaborative effort, the data generated by the computer simulation at the University of Twente were matched with the clinical data collected at Thomas Jefferson University. The following observations were made (9, 13).

**Paresthesias Threshold as a Function of the Spine Level**

The perception threshold is the minimal voltage at which the patient starts to perceive paresthesias from the electrical stimulation. The perception threshold is lowest in the cervical area and highest in the midthoracic area. The curve of the perception thresholds suggests that there is a relationship between the thresholds and spinal levels of implanted electrodes. This relationship can be determined by the distance between the nerve fibers in the spinal cord and the electrode contacts. The most significant factor determining this distance is the thickness of the CSF layer dorsal to the cord. This can be seen in Fig. 2 where the average perception thresholds are graphically represented together with the measurements of dorsal depth of CSF layer. The two variables were found to have a covariance coefficient of 0.99, which is highly significant (24).

**Effects of Electrode Position and Inter electrode Distance**

Paresthesias that cover a broad area of the body are more desirable than paresthesias confined to a small body segment. In general, electrode combinations that stimulate large body areas reflect stimulation of the dorsal columns; combinations that cover only limited segments are usually the result of dorsal root stimulation. Since a larger area of stimulation increases the likelihood of completely covering the painful segment, combinations that cover a large area of the body are usually more desirable. In a study conducted by Barolut and associates, the vast majority of the combinations tested (91%) covered less than 30% of the body surface (13). Only about 28% of them covered an area equivalent to a whole lower extremity. There was a definite increase in the amount of body surface area covered by stimulation when midline-placed contacts were matched against contacts placed laterally. The number of paresthesias felt symmetrically in both lower extremities also markedly decreased with laterally placed contacts. As expected, none of the combinations where the contacts were more than 5 mm from midline yielded contralateral responses. The most successful sensory stimulation for pain control is obtained when the stimulation is confined to the large myelinated sensory fibers. Intraspinal this is best accomplished by stimulating the dorsal columns. Radicular stimulation usually interferes with this, most commonly because segmentary motor stimulation becomes excessive before the paresthesias can completely cover the painful area. For a successful stimulation, therefore, most of the current has to be directed to the area within 2 mm to 3 mm on each side of the physiological midline. The clinical data showed that there is a difference in stimulation threshold between electrodes located in midline or laterally. In the author’s series, the average perception threshold for midline located electrodes was 1.7V, whereas for electrodes placed more than 5 mm from midline it was 0.8V. This difference, as confirmed by the computer model, is most likely attributable to the preferential activation of dorsal root fibers as the electrodes move laterally.

The computer model predicted that the minimum
activation threshold for dorsal column fibers occurred with an electrode separation below 10 mm and that by increasing the interelectrode distance one would increase preferential stimulation for the dorsal root fibers.

Barolat and colleagues analyzed the electrode combinations and found that, with bipolar stimulation, the percentage of body surface covered by stimulation-induced paresthesias decreases with increasing distance between two electrode contacts (13). In their study, the probability of obtaining paresthesias covering a large area of the body, such as both lower extremities, were 14% to 15% with an interelectrode distance of 6 to 30 mm, but only 4% when the contacts are farther than 50 mm apart (13). Conversely, coverage of a small area (less than 10%) of the body was obtained in 51% of combinations with intercontact distance of more than 50 mm vs. in 28% to 34% of the combinations with the contacts less than 30 mm apart. Increasing intercontact distance also seemed to result in a slight increase in the perception threshold; the usage range, however, was not significantly affected due to a similar parallel increase in the discomfort threshold.

CLINICAL CORRELATIONS OF THE STIMULATED STRUCTURES

While initially the term dorsal column stimulation was used 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, it has now become clear that applying electrical fields to the dorsal epidural space activates a larger number of neural structures both inside and outside the spinal cord. The spinal canal and its contents constitute a nonhomogeneous conductor with several nervous and nonnervous structures that, when stimulated electrically, give rise to a variety of responses (Fig. 5). Knowledge of the different type of responses and their correlation with the underlying anatomical substrate is of paramount importance in implementing strategies for spinal cord stimulation. The implanter must also learn how to recognize the effects of mechanical stimulation of the various intraspinal structures, since they can provide invaluable help during the electrode insertion and manipulation.

Mechanical pressure on the dura usually gives rise

Figure 3. Summary of clinical responses of various intraspinal structures to epidural stimulation through dorsally placed electrodes
to a sharp pain that is perceived in the axial midline at the level of the stimulus. The pain can be excruciating if adhesions are encountered in the epidural space. Stimulation of the exiting nerve root, instead, gives rise to a sharp pain felt in the back and in the dermatomal distribution, usually the abdomen or lateral chest wall for a thoracic electrode placement. Electrical stimulation of the ligamentum flavum can also result in a painful sensation perceived in the axial midline. This has constituted a limiting factor in raising the stimulation voltage in patients with percutaneous implanted electrodes because, unlike the plate electrodes, the electrical stimulation is distributed circumferentially.

The width of the CSF space is the single most important factor in determining the electrical parameters, particularly the perception threshold as well as some aspects of the current distribution within the neural structures. It is a common observation that the perception threshold significantly fluctuates between the recumbent and upright position. The stimulation intensity increases substantially when the patient changes from a standing or sitting to a supine position. This can be entirely explained by change in position of the spinal cord in the transverse plane with the resulting changes in the thickness of the dorsal CSF space. The changes in threshold can be in the magnitude of 1V to 2V and can be responsible for either severe jolting or complete loss of stimulation. Acknowledgement of this important factor has lead the manufacturer of the only lithium-powered spinal cord stimulator currently on the market to program two different voltage settings in the hand-held magnet that the patients carry with them. As shown in Fig. 4, with increasing thickness of the CSF layer, dorsal root fibers are more selectively activated than dorsal column fibers.

Stimulation of the large myelinated afferent fibers at the intraspinal level can occur in four different areas: the dorsal root, the dorsal root entry-zone, the dorsal horn, and the dorsal columns. Such stimulation is characterized by tingling paresthesias that are always ipsilateral to the stimulating electrode (Fig. 3). If the stimulation voltage is increased, discomfort and pain occur. Pain is due to overstimulation of the lemniscal pathway and not to activation of the spinthalamic tract. It is important to differentiate activation of the segmentary large myelinated afferents (dorsal root entry-zone/dorsal horn) from activation of the ascending long tracts in the dorsal columns. Activation of the segmentary afferents always gives rise to paresthesias located in the radicular dermatome adjacent to the level of the electrode. For electrodes in the thoracic area, this usually means paresthesias along the anterior chest wall. If the electrode is placed at T12 or L1, however, this could result in paresthesias along the anterior aspect of the thigh or in the inguinal area. In the cervical spine, paresthesias will be elicited in various segments of the upper extremity. The stimulation threshold for the segmentary system is lower than the one for the dorsal columns, and usually ranges from 0.2 to 0.5V.

Differentiation between stimulation of the dorsal root, dorsal root entry-zone, or dorsal horn can be exceedingly difficult. Dorsal root stimulation can be expected if the electrode is placed laterally in the spinal canal. An early recruitment of the segmentary motor fibers (from current spread through the CSF to the anterior roots) associated with sensory paresthesias can also be indicative of stimulation of the root filaments. One can assume stimulation of the dorsal root entry-zone and/or dorsal horn if the electrode is placed near midline and segmentary paresthesias are rapidly followed by activation of the dorsal columns with a small voltage increment. Stimulation of the longitudinal fibers of the dorsal columns is characterized by paresthesias occurring in areas of the body caudal to the level of the electrode; the paresthesias are always ipsilateral to the electrode. The exact distribution of the paresthesias varies with the level of the electrode and with some degree of individual variability (14). In some individuals, activation of the dorsal columns gives rise to

![Figure 4](image-url)  
**Figure 4.** Dorsal column and dorsal root fibers have different excitation thresholds according to the distance between electrode and spinal cord.
a smooth tingling sensation that is uniformly distributed in all the dermatomes caudal to the implanted electrode. In the author's experience, this situation is usually accompanied by pain relief. Other individuals, fortunately a minority, perceive the stimulation with a patchy distribution, affecting separate body segments that are not connected by paresthesias. This is an empirical observation, and no anatomical or physiological explanation has been put forward. These individuals, in the author's experience, do not have any neurological factors that can be identified as predictors. Unfortunately, in this scenario the pain relief is usually minimal or nonexistent.

Activation of the dorsal columns usually occurs at a threshold that is at least 0.5-1 volt higher than the segmentary pathway. A thicker dorsal CSF space usually favors more selective activation of the segmentary sensory system as opposed to the dorsal column fibers (Fig. 2). In this instance, although acutely one might be able to activate both systems simultaneously, after a few weeks of stimulation the paresthesias will invariably become confined to a segmentary band. For this reason, electrode placement in the upper thoracic spine (where the CSF space is the widest) seldom results in satisfactory long-term stimulation of the dorsal lemniscal pathway. In the presence of a narrow CSF space (less than 1.0 mm), conversely, the computer model predicts that the order of recruitment can be reversed and medial dorsal column fibers can be stimulated first (9). This agrees with the clinical finding that stimulation through a midline-placed electrode in the midthoracic area (where the dorsal CSF space is the thinnest) can be perceived initially in the lower extremities.

In most clinical situations one observes a mixture of dorsal column, dorsal root entry-zone, and dorsal root stimulation. This is true particularly with electrodes placed in the low thoracic-upper lumbar area (T11-T12, L1), where the spinal cord tapers into the conus medullaris and the cauda equina nerve roots are a prominent component of the intraspinal structures. The author also believes that cervical SCS for upper-extremity pain mostly reflects stimulation of the segmentary sensory pathway, whereas stimulation at the T9-T10 level for lower extremities pain is mostly the result of true activation of the dorsal column pathways.

Stimulation of the motor structures results in muscular contractions (Fig. 2). Activation of the segmentary motor system (ventral root/motor neurons) results in muscular contractions in the sclerotomical distribution of the stimulated segment. Activation of the descending corticospinal pathways, instead, triggers muscle contractions in segments caudal to the level of the electrode. With laterally placed electrodes, stimulation of the segmentary motor system can occur at a threshold equal to or less than that for large myelinated afferents. This invariably results in unpleasant contractions that can completely deny the benefits of the stimulation. In the vast majority of patients, stimulation over the dorsal columns does not result in activation of the motor system unless the stimulation is increased to a much higher voltage. The author, however, has encountered sporadic instances where, even with a perfectly placed midline electrode, activation of the motor system occurred simultaneously with the sensory system. In these rare instances, pain-relieving dorsal column stimulation cannot be implemented successfully.

CONCLUSION

Electrical stimulation of the nervous system is gaining solid acceptance in the management of chronic pain syndromes as well as being investigated for other conditions such as peripheral vascular disease, intractable angina pectoris, and epilepsy (1, 2, 25-29). The spinal cord and particularly the large myelinated afferent system are currently the most common target of invasive electrical stimulation. Although initially electrodes were implanted subdurally or within the dural layers, today the vast majority of spinal cord stimulation is performed through epidurally implanted electrodes. Due to the complexity of the intraspinal structures, the activation of electrodes in the dorsal epidural space generates complex field potentials, with stimulation of both neural and nonneural elements. The implant surgeon must have a thorough knowledge of these factors to be able to understand the clinical reactions encountered during the implantation and to be able to successfully implement the modality. The work of several investigators has clarified, at both a practical and a theoretical level, some of the issues related to the complexity of epidural stimulation of intraspinal structures. The cooperation between the neuroimplant program at Thomas Jefferson University (USA) and the engineering group at the University of
Twente (the Netherlands) has allowed a comparison of the computer model simulation of the spinal cord with the data from a large number of carefully analyzed clinical observations. The resulting knowledge has provided a greater insight on the response of the intraspinal structures to electrical stimulation.

It is clear that the most important factor in determining the current distribution within the spinal canal is the depth of the dorsal CSF layer. It not only determines the overall threshold of activation of the neural structures, but it also contributes to their individual excitation thresholds. The other significant factor is the size and orientation of the nerve fibers: Larger fibers are recruited first; those that cross the electrical field transversely have a lower threshold than fibers that run longitudinally. Consequently, the transverse segmentary portion of the afferent system tends to be stimulated preferentially. If this is not desirable, great attention must be paid both in the placement of the electrode and in the selection of the appropriate electrical parameters of stimulation. Future advances in electrical stimulation of the nervous system will consist in developing electrode arrays and electrical current delivery modes that will allow an individual to selectively activate individual pathways.

REFERENCES


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