Spinal nerve root stimulation

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Spinal nerve root stimulation is a recently developed form of neuromodulation used for the treatment of chronic pain conditions. Unlike spinal cord stimulation, in which electrical impulses are directed at the dorsal columns, spinal nerve root stimulation guides electrical current directly to one or more nerve roots. There are a variety of techniques by which this can be accomplished, yet no consistent terminology to describe these variations exists. In this review, the authors group the various techniques according to anatomical approach, define each category, describe and illustrate each of the techniques, review the available reports on their uses, and discuss the advantages and disadvantages of each one.

KEY WORDS • pain • neuromodulation • spinal nerve root stimulation • intraspinal nerve root stimulation

NEUROMODULATION is the therapeutic alteration of activity in pain pathways with the use of an implantable device. Although the process of neuromodulation is not completely understood, it is thought to involve both inhibition and activation of relevant neural circuitry. In 1967, the first spinal cord stimulator was placed for the management of chronic pain. Since then, SCS has been used for conditions such as radiculopathy, peripheral neuropathy, peripheral vascular disease, chronic unstable angina, and complex regional pain syndrome.

For SCS, an electrical current is applied to the dorsal columns, creating a tingling sensation in the dermatomes whose afferent fibers traverse the regions being stimulated. Through ill-defined mechanisms, this barrage of nonpainful sensation attenuates the patient’s perception of pain; instead of feeling pain, the patient feels nonpainful paresthesias in the affected areas. For stimulation to be effective, the area of paresthesia must overlap the area of pain. Although in the initial SCS report electrode placement in the subdural space was described, later investigations revealed that the epidural space was a more optimal location.

Although SCS has provided relief in a variety of painful conditions, it still has many limitations, including electrode migration, problems with electrode durability, and postural stimulation variability. In addition, SCS provides incomplete and/or inconsistent coverage for areas such as the low back, buttock, feet, groin, pelvis, and neck. Because the stimulator’s electrical current is limited in its ability to penetrate the spinal cord, stimulation is much less effective for pathways deep within the cord. Thus, some areas, such as those representing the S2–5 dermatomes, are almost completely out of reach.

In recent years, with technological advancements and novel electrode placements along nondorsal column structures, practitioners have begun to address some of these limitations. The use of PNS enables the application of stimulation to a particular peripheral nerve distribution. Occipital neuralgia, trigeminal neuropathic pain, and other painful neuralgias are examples of disorders amenable to treatment with PNS. Of course, PNS has its limitations, including the need for surgical access to the target nerve and restriction of pain relief to the distribution of the target nerve. Furthermore, peripheral nerve stimulators are often needed in regions of the body such as the neck or extremities that are highly mobile, placing high levels of stress along the course of the electrode systems.

Spinal nerve root stimulation has emerged as another treatment option. Like PNS, this form of neurostimulation provides pain relief in areas inaccessible to SCS. Unlike PNS, however, spinal nerve root stimulators are located along the relatively stable and immobile spine. Numerous electrode placement strategies have been developed to accomplish spinal nerve root stimulation, including intraspinal, transforaminal, transspinal, and extraforaminal nerve root stimulation. In this review we discuss the anatomy, techniques, advantages and disadvantages, and clinical studies available for each of these types of spinal nerve root stimulation. (See Table 1.)

Intraspinal Nerve Root Stimulation

Intraspinal nerve root stimulation uses an electrode located completely within the spinal canal, a placement in which the device preferentially stimulates the dorsal spinal rootlets (Fig. 1). In this fashion, stimulation paresthesias can be focused solely within the receptive fields of these rootlets. Depending on the length of the electrode, one, two, or even several spinal segments may be targeted selectively.
Surgical Technique

For the percutaneous retrograde approach to target the lumbosacral nerve roots, the introducer needle is directed into the epidural space at a lumbar level. Once placed, the electrode is passed in a retrograde fashion (toward the sacrum) and advanced to a location parallel to and overlying the lumbar and/or sacral nerve roots. In the original description, the investigators stated that up to two adjacent segmental nerve root distributions could be stimulated simultaneously. Contraindications to this approach include epidural fibrosis, spina bifida occulta, lateral and central stenosis, spondylosis, and spondylolisthesis. For the percutaneous anterograde approach to target the lumbosacral nerve roots, the introducer needle is directed through the sacral hiatus into the epidural space (Fig. 2). Once placed, the electrode is passed in an anterograde direction (toward the head) and advanced to the appropriate location. Although these initial descriptions of spinal nerve root stimulation were limited to the lumbosacral spine, the same techniques may be used to place intraspinal nerve root stimulators almost anywhere along the spinal axis.

Clinical Studies

In early reports of this technique, investigators described anterograde electrode placement along lumbar nerve roots through a laminotomy to treat intractable low-back pain. In later investigations both anterograde and retrograde percutaneous electrode placement methods were described. There are a number of indications for the cephalocaudal approach for nerve root stimulation; these include pelvic pain and perineal pain of urological origin, pelvic motor dysfunction, urinary urge incontinence, detrusor dysfunction, and interstitial cystitis. Before the advent of this technique, chronic pain management in the sacral dermatomes had primarily focused on transsacral extraforaminal approaches to the nerve root (see later discussion). Because of the unique anatomy of

TABLE 1

<table>
<thead>
<tr>
<th>Category</th>
<th>Intraspinal</th>
<th>Transforaminal</th>
<th>Extraforaminal</th>
<th>Transspinal</th>
</tr>
</thead>
<tbody>
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<td>indicated</td>
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<td>iliouinguinal neuralgia</td>
<td>urinary urge incontinence</td>
<td>described in cadavers only</td>
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<td></td>
<td>pelvic motor dysfunction</td>
<td>discogenic back pain</td>
<td>urgency–frequency syndromes</td>
<td></td>
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<tr>
<td></td>
<td>urinary urge incontinence</td>
<td>FBSS</td>
<td>urinary retention, pelvic floor muscle overactivity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>detrusor dysfunction</td>
<td>interstitial cystitis</td>
<td>Fowler syndrome, fecal incontinence</td>
<td></td>
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<tr>
<td></td>
<td>epididymoorchialgia, vulvodynia, bilat foot pain, FBSS</td>
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<td>interstitial cystitis, cervical stenosis</td>
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<tr>
<td>contraindicated</td>
<td>epidural fibrosis, spina bifida occulta stenosis, spondylosis spondylolisthesis</td>
<td>epidural fibrosis spina bifida occulta stenosis, spondylosis spondylolisthesis</td>
<td>foraminial stenosis obese patient w/ small neck</td>
<td>unknown</td>
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</tbody>
</table>

FIG. 1. Anteroposterior radiograph showing an intraspinal nerve root stimulator electrode placed on the right side of T-4. The electrode is located completely within the spinal canal, and stimulates the T3–5 dorsal spinal rootlets.

FIG. 2. Photograph of a lumbosacral spine model with cutaway sacral laminectomy used to demonstrate the technique for anterograde placement of an intraspinal sacral nerve root stimulator electrode on the right side through the sacral hiatus.
Spinal nerve root stimulation

the sacral nerve roots, the latter approach inconsistently provided paresthesia to the appropriate area.

Anterograde intraspinal nerve root stimulators placed via the sacral hiatus have been used to treat the pelvic pain syndromes epididymoorchialgia and vulvodynia. In another report, investigators described the successful use of this technique to target more rostral lumbar and sacral levels in a patient with bilateral foot pain. More rostral placement of the intraspinal nerve root electrodes, at the L1–2 level, enabled a series of patients with axial low-back pain from FBSS to experience pain relief. Placement of the electrodes at the T3–4 level produced analgesia for a patient with chest wall pain, although the exact electrode placement technique was not reported.

Last, the dorsal root ganglion is another theoretical target for intraspinal nerve root stimulation. Whereas dorsal column stimulation typically applies current to pathways mediating touch, vibration, and proprioception (dorsal columns), stimulation of the dorsal root ganglion theoretically applies current to pathways mediating temperature (spinothalamic tract) as well, pathways that are normally out of reach for SCS. Thus, deranged temperature sensations characteristic of neuropathic pains can be attenuated by neurostimulation in this manner.

Transforaminal Nerve Root Stimulation

Transforaminal nerve root stimulation uses an electrode placed within the neural foramen through the spinal canal (Fig. 3). In this fashion, electrical current is applied directly to the nerve root, dorsal root ganglion, and spinal nerve within the foramen itself. Thus, stimulation paresthesias can be focused within the distribution of a single spinal segment.

Surgical Technique

Anatomically, the procedure is initially similar to retrograde intraspinal nerve root stimulation; the electrode is first placed into the spinal canal in an identical fashion. Subsequently, however, the electrode is steered out of the spinal canal into the neural foramen so that it lies adjacent to the intraforaminal structures. In this fashion, one or more (with additional electrodes) thoracic, lumbar, and/or sacral foramina can be cannulated (Fig. 4).
Clinical Studies

The transforaminal technique has been described in a number of reports. With such an approach, it has been possible to target thoracic, lumbar, and sacral nerve roots. Using the technique described earlier, patients with ilioinguinal neuralgia, discogenic back pain, FBSS, and interstitial cystitis experienced alleviation of their symptoms. The exact pattern of electrodes used depends on the distribution of the patient’s pain and pattern of paresthesias generated by the resultant electrical stimulation during the procedure. In general, most patients with pelvic pain syndromes have a favorable response to bilateral S-2 and/or S-3 electrodes. Of course, a variety of electrode patterns can be used, and can include more caudal nerve roots as well, depending on the needs of the patient.

Possible complications of the transforaminal approach are similar to those of the intraspinal approach, including cerebrospinal fluid leakage and inappropriate placement of the stimulator in the intrathecal sac. In addition, because the electrode must turn into the foramen, nerve root damage is also a concern.

Extraforaminal Nerve Root Stimulation

The extraforaminal technique for nerve root stimulation involves stimulating the nerve root from an “outside-in” approach. That is, the electrode is directed into the foramen from outside the spine. In this manner, the electrode is not introduced into the spinal canal prior to entering the neural foramen (Fig. 5).

Surgical Technique

The extraforaminal approach has historically been used for access to the sacral nerve roots and more recently, in one case report, to stimulate cervical nerve roots. Sacral nerve stimulation has been an important advancement in neuromodulation of urinary and pelvic dysfunction, and will be discussed in detail in this section.

Early efforts at sacral nerve stimulation involved placement of an electrode into the S-3 foramen via a posterior approach after surgical exposure of the posterior aspect of the sacrum. Because the electrode is placed directly into the foramen through the incision, no epidural access is initially required. The two most notable limitations of this technique are technical issues with regard to securing the temporary lead, reliably locating the S-3 foramen, and the excessive invasiveness of the procedure. Modifications such as the use of fluoroscopy to localize the S-3 foramen, the use of a much smaller incision, and the introduction of more secure leads have addressed many of the limitations of this technique.

There has been one report of cervical extraforaminal nerve root stimulation; this is the only published description of cervical nerve root stimulation for pain relief. Patients in whom other methods of nerve root stimulation are contraindicated, such as those with scarring from previous surgery or severe spondylosis, may be candidates for this technique. In preparation for the procedure, a supine patient’s cervical foramen is identified using fluoroscopy. The introducer needle is then advanced in a trajectory parallel to the nerve root, into the posterolateral aspect of the foramen, avoiding the adjacent neurovascular structures (Fig. 6). The electrode is placed through the needle, which is then removed, leaving the stimulation electrode posterior and parallel to the nerve root. Risks include the following: pneumothorax; vertebral and carotid artery laceration; and spinal cord, accessory nerve, and cervical nerve root injury. Relative contraindications include foraminal stenosis, which may increase the risk of nerve root injury, and obese, short-necked stature, which may increase the risk of neurovascular injury.

Clinical Studies

The first attempts at extraforaminal sacral nerve root stimulation involved placement of the electrodes along the ventral roots to improve bladder function. Patients with tetraplegia who suffered from bladder dysfunction were reported to have decreased residual volumes and reduced incidences of urinary tract infections after ventral root stimulation. More recently, a large study showed that both sacral deafferentation and anterior root stimulation could also ameliorate urinary dysfunction in paraplegic patients. Although ventral nerve root stimulation is effective for improving bladder function, it can be associated with cerebrospinal fluid leakage, sacral root injury, and postoperative urinary tract infection.

Dorsal sacral nerve root stimulation has also been proven to be effective for urinary and other pelvic dys-
functions, while maintaining a more acceptable side-effect profile than ventral nerve root stimulation. Extraforaminal sacral nerve root stimulation has been used to treat urinary urge incontinence,2,34 urgency–frequency syndromes,21 urinary retention,21 pelvic floor muscle overactivity,31 Fowler syndrome,21 fecal incontinence,21 and interstitial cystitis.9,22,32,33,34 In many chronic voiding dysfunctions, there is a discoordination of reflexes between the bladder, sphincter, and pelvic floor muscles.13 Urinary retention syndromes can be due to either detrusor contraction or bladder outlet obstruction, both of which are amenable to extraforaminal sacral nerve root stimulation. In a multicenter trial conducted in 177 patients with urinary retention, extraforaminal nerve root stimulation resulted both in symptomatic relief after 1 year and a reduction in the number of patients who needed to self-catheterize.22 A similar improvement in voiding function was described after sacral nerve root neuromodulation in patients with nonobstructive urinary retention.1,35

Other indications for extraforaminal sacral nerve root neuromodulation are fecal incontinence and interstitial cystitis.31 Urgency fecal incontinence, which is defined as fecal loss at the first urge to defecate, responds to sacral nerve root electrical stimulation in patients with intact sphincters.19,20,26 Similarly, magnetic sacral nerve root stimulation can also benefit patients with fecal incontinence.28 Interstitial cystitis, a clinical condition characterized by urinary frequency, urgency, intermittent bladder discomfort, and chronic pelvic pain has recently been shown to be responsive to extraforaminal sacral nerve root stimulation.40 Women with intractable interstitial cystitis who were treated with percutaneous sacral nerve root stimulation experienced a decrease in frequency, nocturia, and mean bladder pressure.27 In more recent studies it was found that sacral nerve root stimulation was beneficial in both chronic and refractory interstitial cystitis.14,40 Thus, extraforaminal sacral nerve root stimulation appears to be an appropriate alternative in patients with medically refractory interstitial cystitis.

Finally, there has been only one report in the literature describing extraforaminal stimulation of cervical nerve roots for the treatment of pain.16 The patient in this case presented with a numbness and burning in his left arm caused by a herniated disc and central spinal stenosis. A cervical fusion provided no relief, and an SCS lead could not be placed because of the stenosis. This patient attained acceptable pain relief following placement of an extraforaminal nerve root stimulator electrode.

**Transspinal Nerve Root Stimulation**

Transspinal nerve root stimulation involves placement of an electrode within the neural foramen from the contralateral side (Fig. 7). This approach has been described in cadavers only and has not yet been reported in clinical trials.8 However, this technique offers theoretical anatomical advantages over other options for the placement of certain nerve root stimulator electrodes. For example, the transspinal technique readily permits the placement of electrodes in the cervical or high thoracic neural foramina, a difficult if not impossible task with transforaminal techniques.

**Surgical Technique**

In the transspinal approach, the introducer needle enters the skin in a paramedian fashion, contralateral to and at the level of the target nerve root foramen. The needle is advanced through the interlaminar space in a direction roughly parallel to the target nerve root, until the epidural space is encountered along the midline. The electrode is then advanced laterally through the epidural space until it enters the desired neural foramen adjacent to the targeted nerve root. The cervical and upper thoracic nerves exit the spinal canal in a fairly perpendicular fashion, which is ideally suited to the transspinal approach. Unfortunately, the location of the vertebral artery along the upper cervical spine and the attendant risk of vascular injury precludes the use of the transspinal approach above C-5.5

**Conclusions**

Spinal nerve root stimulation is an important addition to the armamentarium of neurostimulation techniques. It provides the selectivity of PNS with the ease of placement and durability of SCS. In this report we have classified the different forms of nerve root stimulation according to method of electrode placement, described the techniques,
and reviewed the available clinical studies. Future technological and methodological advancements in neurostimulation should further enhance the ability of the pain specialist to treat even more difficult and inaccessible chronic pain conditions effectively.

References


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