Neurostimulation Techniques for Painful Peripheral Nerve Disorders

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KEYWORDS

- Extraforaminal spinal nerve root stimulation
- Intraspinal nerve root stimulation • Pain
- Peripheral nerve field stimulation
- Peripheral nerve stimulation
- Spinal nerve root stimulation
- Subcutaneous peripheral nerve stimulation
- Transforaminal spinal nerve root stimulation
- Trans-spinal nerve root stimulation

The problem of pain in peripheral nerve injuries has presented a unique challenge to physicians throughout history. From Mitchell's earliest descriptions of causalgia in the 1800s,[1] the treatment of pain in peripheral nerve injuries has involved the work of clinicians, neurologists, psychiatrists, anesthesiologists, and surgeons. The pain of peripheral nerve injuries is often unremitting and agonizing, causing significant physical and psychologic disability in these patients. Furthermore, without adequate treatment, this pain and suffering can be expected to continue throughout life, preventing the patient from working or performing many activities of daily living. Many treatments and treatment modalities have been developed through the years to treat these pains, such as opiates, anticonvulsants, antidepressants, and physical and psychologic therapies, but for some patients these provide inadequate relief from their pain.

The gate control theory of pain, proposed in the 1960s, suggested that altering the function of certain sensory pathways in the spinal cord could attenuate the subjective experience of pain by attenuating the activity in separate but parallel pain pathways.[2] Soon thereafter, the first applications of this concept appeared in people. Neuromodulation, the therapeutic alteration of activity in pain pathways with the use of an implantable device, was reported in 1967 as both peripheral nerve stimulation (PNS)[3] and spinal cord stimulation (SCS).[4] The former enabled the targeting of stimulation paresthesias and subsequent pain relief within a specific peripheral nerve distribution, whereas the latter permitted more regional areas of coverage, such as the lower extremities.

Although the process of neuromodulation still is not understood completely, it is thought to involve both inhibition and activation of relevant neural circuitry, including pain pathways in the dorsal horn nucleus and the autonomic nervous system.[5] More recent studies have elucidated the role of neurotransmitters such as g-aminobutyric acid and adenosine to explain how pain modulation through neurostimulation is accomplished.[5] The success of SCS has been documented in several randomized–control trials and case series[6–9] and has provided the impetus for the development of various techniques to target pain control by applying electrical current to different sensory pathways along the peripheral nervous system. The technique of stimulation along a specific spinal nerve

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root or roots, called spinal nerve root stimulation (SNRS),[10,11] offers the advantages of both SCS and PNS. There are also some pain syndromes that are either not amenable to or are served incompletely by SCS, PNS, or SNRS and for which the technique of subcutaneous peripheral nerve stimulation (SPNS) has emerged. All of these techniques are built on a basic set of underlying principles and techniques for implantation, with a common goal of accurately targeting and treating neuropathic pain while at the same time minimizing unwanted adverse effects. Now, within the context of a comprehensive, multidisciplinary approach to pain management, these neurostimulation techniques may offer hope to those patients for whom pain relief was previously unattainable.

SPINAL CORD STIMULATION

Description

Since its introduction over 40 years ago, SCS has undergone significant advancements in technology and techniques for placement. Although the mechanisms by which electrical stimulation of the dorsal columns and afferent fibers attenuate or modulate a patient's sensation of pain are not understood completely, their efficacy in practice has been established, and SCS techniques have been described in the literature for decades.[5] In general, SCS consists of placing an electrode array in the epidural space along the posterior aspect of the dorsal columns. Any point along the spinal cord is a potential target, but generally, midcervical cord placement allows for upper extremity coverage; lower thoracic cord placement allows for low back and lower extremity coverage, and midthoracic cord placement allows for abdominal and visceral coverage.[12] Individual electrode arrays may be placed over each hemicord, allowing for the independent control of left and right sides separately.

Indications

SCS remains the most commonly used implantable neurostimulation technique for the management of a growing number of pain syndromes and regional pain problems. These include: radiculopathies, failed back surgery syndrome (FBSS), peripheral neuropathy, peripheral vascular disease, chronic unstable angina, pain of spinal origin, and complex regional pain syndrome.[5] It generally is accepted for all types of neurostimulation that if a patient has a surgical option with a good probability of success in providing relief for his or her pain (other than SCS), as in the case of a radiculopathy that correlates anatomically with a herniated lumbar disc on MRI, that the patient undergo the definitive surgical procedure rather than treatment with an implantable device. And although SCS implantation is a relatively safe procedure, less invasive alternatives should be used first, before a patient is recommended for SCS. Formal psychologic evaluation generally is recommended before implantation to rule out psychologic amplifiers of pain.

Technique

A trial of SCS is performed before permanent implantation. The trial involves percutaneous placement of a single, or multiple if necessary, cylindric electrode lead(s) percutaneously under conscious sedation using fluoroscopic guidance. An interlaminar space several levels below the level of desired stimulation is selected, and a spinal needle inserted off the midline to access the epidural space. The electrode then is threaded up to the desired spinal level under fluoroscopic guidance. The exact lead position depends upon the desired pattern of stimulation. For example, midline placement of the electrode generally gives bilateral stimulation paresthesias, whereas lateral placement provides unilateral coverage. The leads then are connected to an external stimulus generator, and the patient reports subjective response to stimulation. The leads may be repositioned to achieve optimal coverage. The patient is discharged home for a trial of stimulation of 1 week in most cases. If the response is favorable, the patient returns for permanent implantation of the electrodes and the implantable pulse generator. For permanent placement, either percutaneous or paddle-type electrodes are used, with the latter used predominantly to minimize the risk of migration. Placement of the paddle electrode requires a small minilaminectomy to be performed, under conscious sedation or general anesthesia. The leads are anchored to the fascia to minimize the risk of migration. The leads then are tunneled to a subcutaneous implantable pulse generator (**Fig. 1**).

Limitations

Electrical stimulation of the spinal cord has some limitations. Lead migration, progressive loss of efficacy over time, and postural variability in stimulation intensity (related to the mobility of the spinal cord within the spinal canal during patient movement) are all examples of potential problems with these systems.[5] In addition, SCS provides incomplete or inconsistent coverage of many areas, which are often problem areas for patients who have chronic pain, including the low back, buttocks, feet, groin, pelvis, and neck.[10] Furthermore, some pathways such as those supplying the S2–5 dermatomes, are located somatotopically deep within the spinal cord, and tend to be out of reach

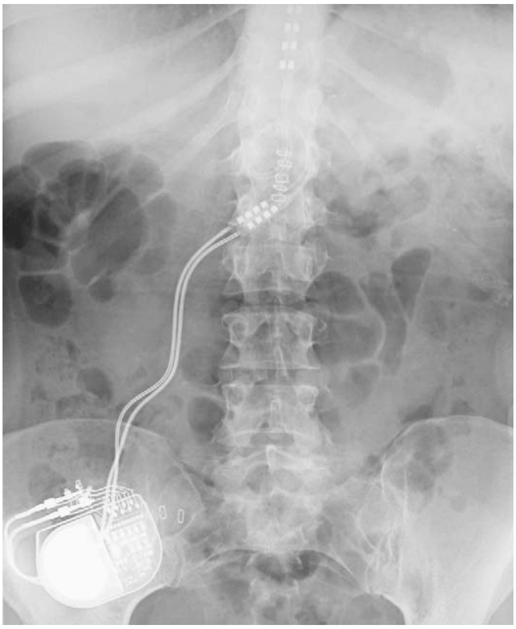

Fig. 1. Anteroposterior radiograph of a patient following placement of a spinal cord stimulator at a low thoracic level and an implantable pulse generator in the buttock to treat complex regional pain syndrome of the lower extremity.

from SCS. Pain syndromes located in these areas are often more responsive to other forms of neurostimulation.

PERIPHERAL NERVE STIMULATION

Description

Disorders of the peripheral nervous system often present a unique challenge to the clinician or surgeon, because the neuropathic pain associated with them can be extremely resistant to typical pain treatments. Painful peripheral nerve disorders often have pain in a particular peripheral nerve distribution, and thus an optimal treatment modality is one that delivers targeted relief to the precise distribution of the pain. This represents the primary advantage of PNS—the ability to focus stimulation paresthesias into the distribution of a specific peripheral nerve without providing unwanted stimulation into other areas. To that end, PNS has undergone several refinements in recent years, enabling the treatment of painful peripheral nerve problems that until fairly recently were either untreatable or poorly treated with traditional SCS techniques.

Indications

Generally speaking, PNS is indicated when the pain is confined to the distribution of a single peripheral nerve, or a limited number of individual peripheral nerves. It is also important that placing the electrode array along the desired peripheral nerve can be done at least as easily as other forms of neurostimulation that also could treat the pain syndrome reasonably. For example, it makes little sense to perform a substantial sciatic nerve exploration at a buttock level to place PNS electrodes, when a spinal cord stimulator could achieve similar pattern of coverage much less invasively.

As techniques for preferentially stimulating the peripheral nervous system have evolved, so too has the spectrum of pathology amenable to treatment by these novel techniques. The use of PNS to treat craniofacial neuropathic pain has emerged in the last decade as a viable treatment modality for this disorder. Because SCS is, for the most part, ineffective in treating craniofacial pain, PNS marks an exiting new therapeutic alternative for patients suffering from a wide array of craniofacial pain syndromes. It most commonly is used to stimulate the occipital and trigeminal regions, for various conditions affecting these nerve distributions. The use of this technique has been reported in the literature to treat postherpetic neuralgia involving the supraorbital and infraorbital nerves,[13–18] as well as occipital nerve[19–22] dysfunction following trauma or surgery, atypical migraines presenting with occipital pain,[23,24] cluster headache,[25] and cervicogenic occipital pain.[23,24,26–28] PNS also may be used to target larger nerves through an open approach.[27] For example, tibial and peroneal nerve stimulation may provide relief of foot pain.

Technique

As with SCS implantation, rigorous methodology for patient selection, including consideration of alternative, less invasive pharmacologic, physical medicine, or psychologic therapies should be applied to ensure the greatest success with peripheral nerve stimulator implantation. Similar to SCS, the same basic paradigm exists for PNS placement anywhere in the body. Following psychologic evaluation, a trial of stimulation is performed. Although not routinely done at the authors' institution, a diagnostic nerve block commonly is performed initially to establish the peripheral nerve contribution to the pain.[23,24]

For percutaneous PNS, electrodes are inserted in the epifascial plane above the muscle under conscious sedation. Four- or eight-contact electrodes are used, depending upon the desired size of electrode array. For craniofacial stimulation, fluoroscopic guidance typically is not required, as the external facial landmarks are adequate for guidance, although it may be used to verify positioning and make fine tune adjustments if coverage is inadequate. For stimulation of the supraorbital nerve, the standard landmarks for insertion are the supraorbital groove or foramen and the supraorbital ridge. For the infraorbital nerve, the infraorbital foramen and the floor of the orbit are used (**Fig. 2**). For the occipital nerve, our entry point is on midline near the occipital protuberance. The curved needle is advanced in a superolateral direction, aiming for the top of the pinna. Thus, the octad electrode overlies the occipital nerves (**Fig. 3**). Following placement, the electrode is connected to an external pulse generator and the patient tested for stimulation-induced paresthesias. Coverage areas also are tested. If the result is satisfactory, the electrode leads are fastened to the skin in a looped fashion with a series of 3-0 silk ties to avoid excessive strain or torque on the electrodes. An anteroposterior and lateral skull radiograph are obtained to document the electrode placement, and the patient then is discharged home for a trial of stimulation of typically 1 week. The authors do not prescribe antibiotic prophylaxis routinely for the trial duration. If the trial provides a distinct benefit, the patient returns for replacement of the temporary electrode with a permanent one. A new electrode then is tunneled to an implantable pulse generator, which is placed subcutaneously in either a buttock or subclavicular location.

For open PNS, the target peripheral nerve is subjected to an external neurolysis with the patient under conscious sedation. Then either a percutaneous or paddle lead is placed adjacent to the nerve (**Fig. 4**). When using a paddle lead, the authors customarily place a layer of fascia between the electrode array and the nerve itself. Intraoperative testing commences, and the electrode positioned is changed as needed to achieve optimal stimulation. Once in position, it is secured with sutures to surrounding tissue planes, and externalized with a disposable extension wire. After wound closure, the patient undergoes a 1-week trial as for the percutaneous system. If successful, the extension wire is discarded, and the lead connected to a nearby implantable pulse generator as described previously. If the trial was unhelpful, the lead is removed and discarded.

Fig. 2. Anteroposterior radiograph of a patient following placement of supraorbital and infraorbital nerve stimulator electrodes to treat trigeminal neuropathic pain resulting from a trigeminal branch injury. Note the position of the electrodes in the vicinity of the nerves as they exit their respective foramina near the orbit.

Limitations

The primary drawback to PNS is lead migration and fracture. Although spinal cord stimulators are placed along the relatively stable and immobile spine, PNS requires sometimes difficult surgical access to the target nerves, which are often 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 system and theoretically contributing to higher rates of electrode migration and malfunction. And while the selective stimulation of a single peripheral nerve may be desired, in cases where broader coverage of a particular area of pain distribution is necessary, a single peripheral nerve stimulator alone may be inadequate.

SPINAL NERVE ROOT STIMULATION

Description

One of the more recent and exciting developments in neurostimulation involves the preferential stimulation of one or more spinal nerve roots directly. Thus, desired stimulation can be targeted to specific radicular distributions while eliminating unwanted paresthesias beyond these specific areas. Numerous electrode placement strategies have been developed to selectively stimulate spinal nerve roots, and previously have been classified to include the intraspinal (anterograde or retrograde), transforaminal, trans-spinal, and extraforaminal techniques.[11] Like SCS, these stimulators are located along the relatively stable and immobile spine, theoretically limiting the risk of electrode migration compared with more peripherally-placed PNS electrodes.

Indications

Intraspinal nerve root stimulation has become a useful technique for treating painful peripheral nerve problems. In this form of SNRS, the electrode is placed in the lateral aspect of the spinal

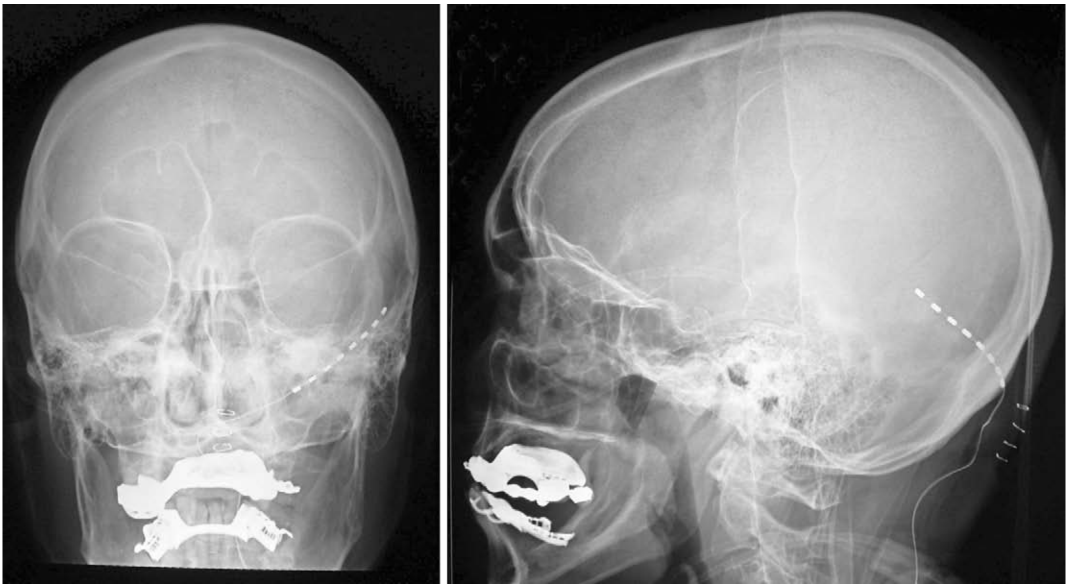

Fig. 3. Anteroposterior (*left*) and lateral (*right*) radiographs of a patient following placement of an occipital nerve stimulator electrode used to treat occipital neuralgia. The electrode array overlies the occipital nerves as they course along the back of the head. Either percutaneous or paddle leads may be used in this location.

canal, overlying the desired dorsal rootlets. In this fashion, stimulation paresthesias are focused along the target nerve root dermatomes, and not along more caudal targets as in dorsal column stimulation. Postherniorrhaphy inguinal neuralgias may be treated with an intraspinal nerve root electrode placed in the lateral spinal canal at the T12-L1 level eccentric to the side of pain (**Fig. 5**). This focuses stimulation paresthesias in the groin region without annoying lower extremity stimulation. The intraspinal retrograde approach has demonstrated applicability in treating pelvic pain,[29] perineal pain of urologic origin,[30] and interstitial cystitis.[31–33]

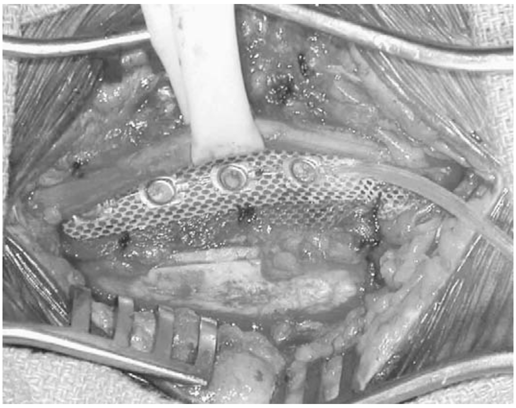

Fig. 4. Intraoperative photograph taken during placement of a tibial nerve stimulator following external neurolysis of the nerve. Although a paddle electrode was used to treat tibial neuralgia in this case, percutaneous electrodes may be used also.

Transforaminal nerve root stimulation is a form of SNRS in which the electrodes are passed through the spinal canal in a retrograde fashion, and steered out into the nerve root foramen. Once in place, the stimulation paresthesias are focused upon the single nerve root and its dorsal root ganglion residing in the target foramen. Although traditional SCS covers the dorsal columns only, stimulating pathways mediating touch, vibration, and proprioception, stimulation of the dorsal root ganglion theoretically applies additional current to spinothalamic tracts mediating temperature sensation.[34,35] Thus, neuropathic pain syndromes that feature predominantly deranged temperature sensation may be served uniquely by the transforaminal technique. Successful transforaminal nerve root stimulation has been reported in patients who have ilioinguinal neuralgia,[36] discogenic back pain,[30] FBSS,[37] and interstitial cystitis.[31–33] The authors have used transforaminal nerve root stimulation to treat foot pain from painful peripheral neuropathy (**Fig. 6**), a notoriously difficult peripheral nerve pain disorder to treat.

Technique

Intraspinal nerve root stimulation can be accomplished through either an anterograde or

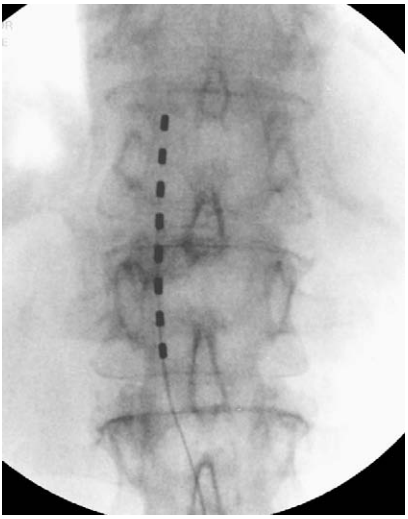

Fig. 5. Intraoperative fluoroscopic image of a patient during placement of a right-sided intraspinal nerve root electrode at the T12-L1 level used to treat postherpetic neuralgia at a groin level. Note the placement of the electrode in the lateral aspect of the spinal canal, overlying the dorsal rootlets before their entry into the dorsal root entry zone. This focuses the stimulation paresthesias into the T12-L1 dermatomes selectively without unwanted stimulation into the dorsal columns or other nerve roots. The authors commonly use this same electrode array to treat postherniorrhaphy inguinal neuralgias when less invasive measures are unhelpful.

retrograde percutaneous approach. In this technique, the electrode is located completely within the spinal canal. In the retrograde approach, the introducer needle is directed into the epidural space and the electrode passed in a retrograde and lateral fashion parallel to and overlying the desired nerve roots.[11,36] In the anterograde approach, the introducer needle is directed through either the interlaminar space or the sacral hiatus using a loss-of-resistance technique. This also can be done through a small laminectomy if percutaneous attempts are unsuccessful. Once the epidural space is entered, the electrode is passed rostrally and then directed laterally over the desired dorsal rootlets.[11,32,38]

Transforaminal nerve root stimulation is accomplished by means of the retrograde percutaneous approach. In this approach, the introducer needle is directed into the epidural space and the electrode passed in a caudal direction and steered into the appropriate neural foramen.[11,32,37] Typically, most patients who have pelvic pain syndromes respond most favorably to bilateral S-2 or S-3 electrodes. Placement in the L3 and L4 foramina results in stimulation

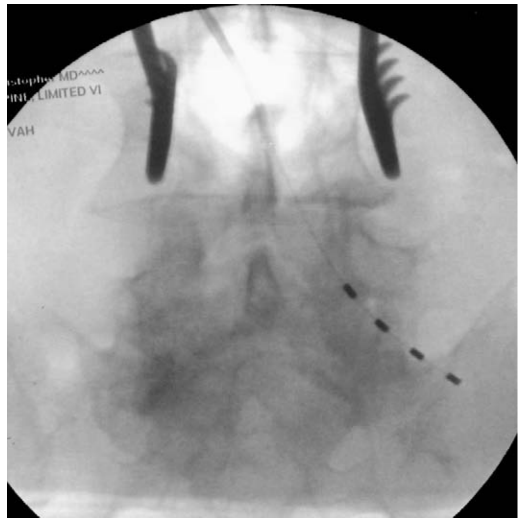

Fig. 6. Intraoperative fluoroscopic image of a patient during placement of a left-sided transforaminal nerve root electrode at the L5 level used to treat a painful peripheral neuropathy. The L5 nerve root was chosen, because the patient's pain was concentrated along the top of his foot. Note placement of the electrode within the neural foramen, in a position overlying both the spinal nerve root and the dorsal root ganglion.

paresthesias focused along the knee, whereas L5 and S1 placement targets the foot. Thus, painful nerve injuries in these locations that prove refractory to less invasive measures may be treated effectively with transforaminal nerve root stimulation.

The trans-spinal technique[11,37,39] involves placement of an electrode into the neural foramen from a contralateral approach. In this technique, the introducer needle is placed in a paramedian fashion on the side contralateral to the desired neural foramen to be accessed. This may be done through either a percutaneous or open approach. The needle is advanced through the interlaminar space oriented parallel to the direction of the targeted nerve root. The epidural space is accessed at the midline, and the electrode then is advanced out laterally through the neural foramen and adjacent to the nerve root (**Fig. 7**). Because the cervical and thoracic nerve roots exit the spinal canal in a rather perpendicular fashion relative to the spinal cord, unlike the lumbosacral nerve roots, which are oriented more parallel, the trans-spinal technique theoretically offers anatomic advantages in accessing the nerve roots in these regions, which has proved difficult using the more traditional transforaminal or intraspinal techniques.

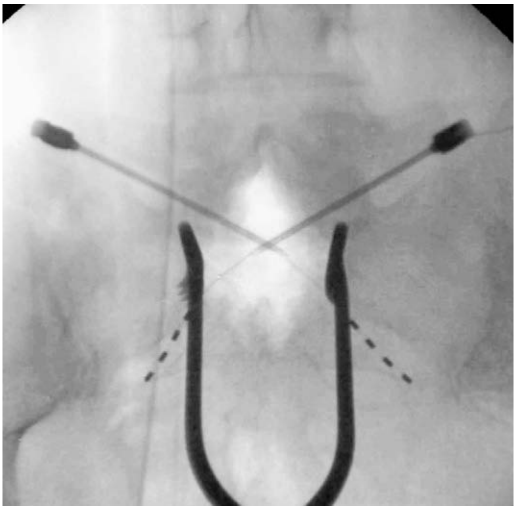

Fig. 7. Intraoperative fluoroscopic image of a patient during placement of bilateral trans-spinal nerve root electrodes at the S1 level used to treat tibial neuralgia. The S1 nerve roots were chosen, because the patient's pain was concentrated along the bottoms of the feet. An earlier trial of spinal cord stimulation was unsuccessful. The epidural space was accessed through a small midline laminectomy. Each electrode was placed through a small stab incision on the contralateral side, aiming in the direction of the target nerve root foramen. Note placement of the electrodes within the neural foramen, in a position overlying both the spinal nerve root and the dorsal root ganglion. As for each of these neurostimulation techniques, this may be done through either a percutaneous or an open approach.

Limitations

The limitations and contraindications to SNRS generally depend on the technique used for placement, although for all of the techniques there is a modestly added risk (beyond the standard risks of traditional SCS placement) of injury to the nerve root itself.[32] Although there may be particular advantages to the use of the trans-spinal technique in the cervicothoracic spine as previously discussed, access to the upper cervical spine above C-5 is contraindicated because of the risk of vertebral artery injury.[37] The most notable limitation for all of these SNRS techniques is a comparative lack of published outcome data for their use. The authors advocate their use by experienced practitioners in neurostimulation methods for specific applications not effectively addressed by more conventional forms of stimulation. A classic example is the use of SCS to treat upper extremity pain, and the supplemental use of a C6-8 intraspinal nerve root stimulator to provide augmented coverage of the hand that may remain uncovered by SCS alone.

SUBCUTANEOUS PERIPHERAL NERVE STIMULATION

Description

Occasionally, patients have pain that cannot be covered adequately by SCS, PNS, or SNRS techniques. In these cases, initial success has been reported using stimulator leads placed subcutaneously in the exact area or region of pain.[40–45] Often this technique is used in conjunction with an implanted SCS or PNS to provide adjunctive coverage of a focal area of pain.

Indications

Clinical reports of SPNS in the limb, inguinal area, and abdomen demonstrate its utility as a primary therapeutic modality.[40–42] In one report, Paicius and colleagues[40] demonstrated significant improvement in quality of life and reduction in opioid requirements following SPNS in patients who had inguinal neuralgia, chronic pancreatitis, and abdominal pain following liver transplantation, all of whom had failed nerve blocks, neurolysis, and medical therapy. In another small series, Goroszeniuk and colleagues[41] reported success in treating patients who had anterior chest wall and intercostal pain following various thoracic surgical procedures. They found that SPNS of 1 to 2 hours daily produced pain relief lasting 12 to 24 hours. Interestingly, these effects of SPNS did not correlate with transcutaneous electrical nerve stimulation, which none of the patients reported to be of any benefit. The authors have used SPNS in the treatment of postamputation stump pain when SCS failed to achieve the appropriate coverage along the painful area (**Fig. 8**).

In the case of chronic abdominal pain, SPNS may be uniquely advantageous, because this pain is often both neuropathic and nociceptive, and peripheral field stimulation covers both the regional dermatomal and visceral innervations that converge at the same spinal cord segment or segments, without the risk of neurologic sequelae possible with SCS. In fact, when SPNS is considered versus SCS in any situation, it offers the significant advantage of avoiding the spinal cord and associated risk of dural compromise and cord or root injury.[40,42] Preliminary studies have suggested that SPNS is quite useful as an adjunct treatment in concert with SCS.[46] For example, in patients who have FBSS and persistent low back and leg pain, SCS often effectively treats the lower extremity component of pain, but provides suboptimal relief for the low back pain. In these cases, the addition of subcutaneous electrodes may provide the necessary stimulation paresthesias and subsequent pain relief in the low back area (**Fig. 9**).

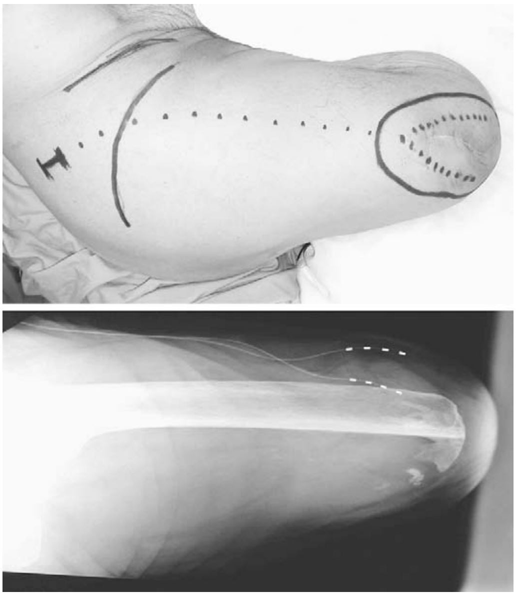

Fig. 8. Intraoperative radiograph (*above*) and postoperative radiograph (*below*) of a patient who underwent placement of subcutaneous peripheral nerve electrodes used to treat postamputation stump pain, located within the encircled region at the distal portion of the limb, adjacent to his healed incision. The curved line along the proximal hip represents the proximal extent of his prosthesis. The authors externalized his trial electrodes proximal to this point so that the prosthesis would not irritate the wires as they exited his skin. This patient had failed an earlier trial of spinal cord stimulation.

Technique

In SPNS, leads are placed subcutaneously at the specific area of pain, with local anesthesia. A trial of stimulation is performed similar to other forms of stimulation. If results are satisfactory, the temporary leads are discarded; permanent leads are placed and then connected to an implantable pulse generator. Most commonly, buttock or subcostal sites are chosen for the implantable pulse generator, depending upon location of the electrodes and patient preference. In cases where an existing PNS or SCS has been implanted and providing desirable coverage in all but a focal area of pain, and an SPNS is being used to cover that specific area, the lead is tunneled to the existing pulse generator.

Limitations

The primary limitation of SPNS is the lack of randomized–control studies or large case series demonstrating its efficacy and potential advantage to existing neuromodulation techniques. Although the preliminary results are promising, larger trials

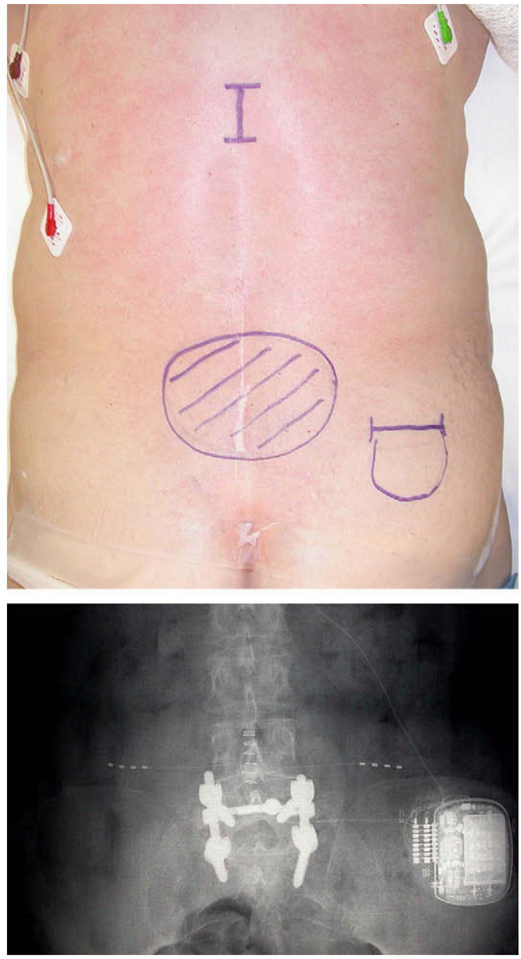

Fig. 9. Intraoperative radiograph (*above*) and postoperative radiograph (*below*) of a patient with failed back surgery syndrome and persistent low back and leg pain. During the spinal cord stimulator trial, the patient obtained excellent relief of the leg pain, but insufficient relief of the low back pain. The authors therefore placed a permanent low-thoracic spinal cord stimulator array (out of the field of view) to get leg coverage and added a supplemental array of subcutaneous peripheral nerve stimulator electrodes along the area of low back pain (*cross-hatched area on the skin*).

are necessary to establish this technique firmly among the neurostimulation options available to the surgeon today. Meanwhile, this may represent an excellent treatment option because of its ease of placement, few risks, and compatibility with existing stimulator systems.

REFERENCES

1. Mitchell SW, Morehouse CR, Keen WW. Gunshot wounds and other injuries of the nerves. Philadelphia: JB Lippincott; 1864. p. 143–57.

2. Melzack R, Wall PD. Pain mechanisms: a new theory. Science 1965;150(699):971–9.
3. Wall PD, Sweet WH. Temporary abolition of pain in man. Science 1967;155:108–9.
4. Shealy CN, Mortimer JT, Reswick J. Electrical inhibition of pain by stimulation of the dorsal column: preliminary clinical reports. Anesth Analg 1967;46: 489–91.
5. Lee AW, Pilitsis JG. Spinal cord stimulation: indications and outcomes. Neurosurg Focus 2006; 21(6):E3, 1–6.
6. Burchiel KJ, Anderson VC, Brown FD, et al. Prospective, multicenter study of spinal cord stimulation for relief of chronic back and extremity pain. Spine 1996;21:2786–94.
7. Kemler MA, Barendse GA, van Kleef M, et al. Spinal cord stimulation in patients with chronic reflex sympathetic dystrophy. N Engl J Med 2000;343:618–24.
8. North RB, Kidd DH, Farrokhi F, et al. Spinal cord stimulation versus repeated lumbosacral spine surgery for chronic pain: a randomized, controlled trial. Neurosurgery 2005;56:98–106.
9. North R, Shipley J, Prager J, et al. American Academy of Pain Medicine. Practice parameters for the use of spinal cord stimulation in the treatment of chronic neuropathic pain. Pain Med 2007;8(Suppl 4): S200–75.
10. Alo KM, Holsheimer J. New trends in neuromodulation for the management of neuropathic pain. Neurosurgery 2002;50:690–704.
11. Haque R, Winfree CJ. Spinal nerve root stimulation. Neurosurg Focus 2006;21(6):E4, 1–7.
12. Khan YN, Raza SS, Khan AE. Application of spinal cord stimulation for the treatment of abdominal visceral pain syndromes: case reports. Neuromodulation 2005;8(1):14–27.
13. Dunteman E. Peripheral nerve stimulation for unremitting ophthalmic postherpetic neuralgia. Neuromodulation 2002;5:32–7.
14. Johnson MD, Burchiel KJ. Peripheral stimulation for treatment of trigeminal postherpetic neuralgia and trigeminal post-traumatic neuropathic pain: a pilot study. Neurosurgery 2004;55:135–42.
15. Slavin KV, Burchiel KJ. Peripheral nerve stimulation for painful nerve injuries. Contemp Neurosurg 1999;21(19):1–6.
16. Slavin KV, Burchiel KJ. Use of long-term nerve stimulation with implanted electrodes in the treatment of intractable craniofacial pain. J Neurosurg 2000;92: 576 [abstract #827].
17. Slavin KV, Nersesyan H, Wess C. Treatment of neuropathic craniofacial pain using peripheral nerve stimulation approach. In: Meglio M, Krames ES, editors. Proceedings of 7th Meeting of International Neuromodulation Society, Rome (Italy), June 10–13, 2005. Bologna (Italy): Medimond; 2005. p. 77–80.
18. Slavin KV, Wess C. Trigeminal branch stimulation for intractable neuropathic pain: technical note. Neuromodulation 2005;8:7–13.
19. Nörenberg E, Winkelmuller W. The epifacial electric stimulation of the occipital nerve in cases of therapy-resistant neuralgia of the occipital nerve. Schmerz 2001;15:197–9 [German].
20. Hammer M, Doleys DM. Perineuromal stimulation in the treatment of occipital neuralgia: a case study. Neuromodulation 2001;4:47–52.
21. Kapural L, Mekhail N, Hayek SM, et al. Occipital nerve electrical stimulation via the midline approach and subcutaneous surgical leads for treatment of severe occipital neuralgia: a pilot study. Anesth Analg 2005;101:171–4.
22. Lou L. Uncommon areas of electrical stimulation. Curr Rev Pain 2000;4:407–12.
23. Slavin KV, Colpan ME, Munawar N, et al. Trigeminal and occipital peripheral nerve stimulation for craniofacial pain: a single-institution experience and review of the literature. Neurosurg Focus 2006; 21(6):E6, 1–5.
24. Slavin KV, Nersesyan H, Wess C. Peripheral neurostimulation for treatment of intractable occipital neuralgia. Neurosurgery 2006;58:112–9.
25. Magis D, Allena M, Bolla M, et al. Occipital nerve stimulation for drug-resistant chronic cluster headache: a prospective pilot study. Lancet Neurol 2007;6:314–21.
26. Weiner RL. Occipital neurostimulation for treatment of intractable headache syndromes. Acta Neurochir Suppl 2007;97:129–33.
27. Weiner RL. Peripheral nerve neurostimulation. Neurosurg Clin N Am 2003;14:401–8.
28. Rodrigo-Royo MD, Azcona JM, Quero J, et al. Peripheral neurostimulation in the management of cervicogenic headaches: four case reports. Neuromodulation 2005;8:241–8.
29. Alo KM, Gohel R, Corey CL. Sacral nerve root stimulation for the treatment of urge incontinence and detrusor dysfunction utilizing a cephalocaudal intraspinal method of lead insertion: a case report. Neuromodulation 2001;4:53–8.
30. Feler CA, Whitworth LA, Fernandez J. Sacral neuromodulation for chronic pain conditions. Anesthesiol Clin North America 2003;21:785–95.
31. Comiter CV. Sacral neuromodulation for the symptomatic treatment of refractory interstitial cystitis: a prospective study. J Urol 2003;169:1369–73.
32. Maher CF, Carey MP, Dwyer PL, et al. Percutaneous sacral nerve root neuromodulation for intractable interstitial cystitis. J Urol 2001;165:884–6.
33. Whitmore KE, Payne CK, Diokno AC, et al. Sacral neuromodulation in patients with interstitial cystitis: a multicenter clinical trial. Int Urogynecol J Pelvic Floor Dysfunct 2003;14:305–9.

34. Yearwood TL. Intraspinal nerve root stimulation for the treatment of axial lumbar spine pain in postlaminotomy syndrome. Presented at the 7th Meeting of the International Neuromodulation Society. Rome, Italy, June 10–13, 2005.
35. Yearwood TL. Neuropathic extremity pain and spinal cord stimulation. Pain Med 2006;7(Suppl 1): S97–102.
36. Alo KM, Yland MJ, Feler C, et al. A study of electrode placement at the cervical and upper thoracic nerve roots using an anatomic trans-spinal approach. Neuromodulation 1999;2:222–7.
37. Alo KM, Yland MJ, Redko V, et al. Lumbar and sacral nerve root stimulation (NRS) in the treatment of chronic pain: a novel anatomic approach and neurostimulation technique. Neuromodulation 1999;2: 23–31.
38. Falco FJ, Rubbani M, Heinbaugh J. Anterograde sacral nerve root stimulation (AS-NRS) via the sacral hiatus: benefits, limitations, and percutaneous implantation technique. Neuromodulation 2003;6: 219–24.
39. Urban BJ, Nashold BS Jr. Combined epidural and peripheral nerve stimulation for relief of pain. Description of technique and preliminary results. J Neurosurg 1982;57:365–9.
40. Pacius PM, Bernstein CA, Lempert-Cohen C. Peripheral nerve field stimulation in chronic abdominal pain. Pain Physician 2006;9:261–6.
41. Goroszeniuk T, Kothari S, Hamann W. Subcutaneous neuromodulating implant targeted at the site of pain. Reg Anesth Pain Med 2006;31:168–71.
42. Goroszeniuk T. Percutaneous insertion of permanent peripheral stimulating electrode in patients with neuropathic pain. Presented at the 6th World Congress of International Neuromodulation Society. Madrid, Spain, June 25–28, 2003.
43. Goroszeniuk T, Kothari S. Targeted external area stimulation. Reg Anesth Pain Med 2004;29(Suppl 2): 98–103.
44. Monti E. Peripheral nerve stimulation: a percutaneous minimally invasive approach. Neuromodulation 2004;7(3):193–6.
45. Stinson LW, Roderer GT, Cross NE, et al. Peripheral subcutaneous electrostimulation for control of intractible postoperative inguinal pain: a case report series. Neuromodulation 2001;4(3):99–104.
46. Bernstein CA, Paicius RM, Barkow SH, et al. Spinal cord stimulation in conjunction with peripheral nerve field stimulation for the treatment of low back and leg pain: a case series. Neuromodulation 2008;11: 116–23.