Spinal Cord Stimulation

44

Ramsin Benyamin, Ricardo Vallejo, and David L. Cedeño

Introduction

Electrical stimulation of the central nervous system (CNS) and peripheral nerves has become the main alternative to neuroablative treatments for alleviating chronic pain. Electrical stimulation of the CNS has mostly involved deep brain stimulation (DBS) and the epidural stimulation of the dorsal spinal cord, generally called spinal cord stimulation (SCS). Since its inception in 1968, SCS has evolved into the neurostimulation technique of choice because of its minimally invasive nature and the proven efficacy for the treatment of chronic painful conditions. SCS covers many indications including failed back surgery syndrome (FBSS), radiculopathies, complex regional pain syndrome (CRPS), peripheral neuropathies, and ischemic limb pain secondary to peripheral vascular disease [1–5]. To date, the field of SCS has evolved into one in which various technologies and stimulation paradigms are available, although a full understanding of the mechanism of action is not known. SCS is useful for treating pain syndromes in which the affected sensory nerves can be targeted via the positioning of the electric field delivered by stimulating leads at a particular segment in the spinal cord associated with the affected nerves. This chapter describes interventional details in the field of SCS with emphasis on available technologies and their application to common indications.

R. Benyamin (✉)
Millennium Pain Center, Bloomington, IL 61704, USA

College of Medicine, University of Illinois, Champaign-Urbana, IL, USA
e-mail: ramsinbenyamin@yahoo.com

R. Vallejo • D.L. Cedeño
Millennium Pain Center, Bloomington, IL 61704, USA

History

Electricity has been used throughout the history to treat painful conditions. The oldest account is from the year 46 AD when Scribonius Largus reported in his *Compositiones Medicae* the use of electricity from a torpedo ray fish (*Torpedo torpedo*) to treat headaches and gout pain [6]. Interestingly, late in the 1700s, Benjamin Franklin used electricity to stimulate muscle action in the limbs of paralytic patients [7]. Direct electrical stimulation of the nervous system was not considered until 1965 when Melzack and Wall proposed the "gate control theory" [8]. In their publication they suggested that pain can be blocked by stimulation of large A-β fibers in order to close the gate to the nociceptive input which is transmitted by the small A-δ and C-fibers. In 1967, Shealy et al. [9] reported that direct current applied to the dorsal spinal cord of cats can block an electrically elicited tetanic stimulation of a peripheral nerve. This report was followed by another in which Shealy et al. [10] reported the first clinical case of spinal cord stimulation (SCS) using a single electrode and a pulsed generator (10–50 Hz, 400 μs pulse width, 0.36–0.52 mA) in a volunteer patient who suffered from cancer-related pain. The first commercially available spinal cord stimulator was developed by Medtronic® (Minneapolis, MN) in 1968 as a result of Shealy's experiments and was based on previous devices used for stimulation of the carotid sinus nerve in the treatment of angina [11]. In 1981, using advanced battery technology, Medtronic® produced the first fully implantable spinal cord stimulator. It was not, however, until 2004 that Boston Scientific® (Marlborough, MA; then Advanced Bionics) introduced the first rechargeable implantable pulse generator (IPG) [12]. Over the years, the field of SCS has mostly evolved around lead designs that incorporate arrays of electrical contacts and software algorithms that provide optimal electrical outputs with the goal of improving coverage. There is, however, a current tendency that revolves around development of stimulation systems that deviate from the conventional stimulation

L. Manchikanti et al. (eds.), *Essentials of Interventional Techniques in Managing Chronic Pain*,
https://doi.org/10.1007/978-3-319-60361-2_44

paradigm based on continuous pulsed stimulation at around 50 Hz. Nevro Corporation (Menlo Park, CA) has introduced an IPG that delivers high frequency pulses (10 kHz) without the common paresthesia felt by patients under conventional stimulation, which is reported to be superior [13, 14]. Recently, stimulation via bursts of electrical pulses (five spikes at 500 Hz per burst pulsed at 40 Hz) has also shown better pain relief than conventional stimulation in preliminary clinical studies [15, 16].

Pathophysiology

- The spinal cord extends from the base of the brain to the level of the second lumbar vertebra (L2). At each particular vertebral level, nerves branch out of the cord into plexus composed of peripheral nerves that innervate different parts of the body.
- Beyond L2 the spinal cord develops into the cauda equina, a collection of nerve roots and nerves that originate at the conus medullaris and continue down into the coccygeal nerves.
- Physiologically, the spinal cord can be segmented into distinctively different sections. Each segment has associated ganglia and nerves that process afferent sensory stimuli on its way to the brain.
- Peripheral nerve injury may develop into chronic neuropathic pain which is exacerbated by innocuous stimuli and otherwise painless stimuli (allodynia and hyperalgesia) [17].
- Nerves are composed of fibers, which contain both myelinated and unmyelinated axons.
  - Myelinated A-δ fibers conduct sensory information from the periphery faster than the unmyelinated sensory C-fibers.
  - Stimuli are conducted to the dorsal root ganglion (DRG) and then into the spinal cord, where the fibers terminate into synapses with interneurons located in the gray matter of the cord.
- Peripheral sensitization occurs as a result of inflammatory processes initiated following the nerve injury. Mast cells, macrophages, and T cells release cytokines and neuropeptides, which ultimately lead to glial activation and feedback responses transmitted into the CNS.
  - Peripheral sensitization involves a reduction in sensitivity thresholds, particularly of the C-fibers resulting in windup phenomenon of the dorsal horn interneurons.
- Nerve injury ultimately leads to reshaping of the response system, which involves changes in gene expression and subsequent protein expression that leads to a phenotype of chronic pain [18].
- Biological and biochemical changes occurring peripherally lead to ectopic activity involving uninjured adjacent neurons [19].
  - Cell membrane components particularly ion channels are largely affected, leading to spontaneous firing bursts in the neurons without external stimulus.
- Abnormal stimuli from peripheral fibers translate into changes in the central nervous system at the level of the spinal cord (dorsal horn) and synaptic plasticity (homo- and hetero-synaptic potentiation).
  - These changes contribute to central sensitization, invoking plasticity of the CNS that leads to the establishment of a neuropathic chronic pain state.
  - Key factors associated with synaptic plasticity are calcium receptors (both ionotropic and voltage-gated) as well as glutamate receptors (NMDA, AMPA, mGluR), cytokines, and their receptors (substance P, ephrins, BDNF, kinins, protein kinases, and particular ion channels).
  - Another factor associated with central sensitization is the loss of inhibitory regulation in the dorsal horn. Peripheral nerve injury results in the glutamate, γ-amino butyric acid (GABA)-induced reduction of inhibitory postsynaptic currents [20], which is partially associated with the loss of GABAergic interneurons in the dorsal horn [21].
  - Glial cells also release cytokines that affect GABA-regulated inhibition by altering the anion reversal potential of the GABAergic neurons [22, 23].
    - Following peripheral nerve injury, microglia are activated in the dorsal horn, at the cord segment corresponding to the injured nerve as a result of macrophage infiltration and T-cell recruitment.
- Changes in the spinal cord result in supraspinal effects. Brain imaging techniques indicate that some regions in the brain (a "pain matrix") are activated in response to noxious stimuli.
  - Some components of the supraspinal pain matrix include the rostroventral medulla, locus coeruleus, periaqueductal gray, medial prefrontal cortex, nucleus accumbens, insula, amygdala, anterior cingulate cortex, and cerebellum.

Evidence Base

- Evidence is determined based on a best evidence synthesis [15], ranging from Levels I to V.
  - Level I is obtained from multiple, relevant, high-quality randomized controlled trials (RCTs) or diagnostic accuracy evidence obtained from multiple high-quality diagnostic accuracy studies.
  - Level II is obtained from at least one relevant high-quality RCT, or multiple relevant moderate- or low-quality RCTs, or the evidence was obtained from at least one high-quality diagnostic accuracy study or, for diagnostic interventions, multiple moderate- or low-quality diagnostic accuracy studies.

  - Level III incorporates not only evidence from randomized trials but also from non-randomized trials.
  - Levels IV and V are based on observational studies and consensus.
- Evidence for SCS is summarized in Table 44.1. SCS has been used for various morbidities.
  - A 20-year systematic review [5] of SCS indicates that the estimated success rate of SCS is 84% in CRPS, 82% in postherpetic neuralgia, 77% in ischemic limb pain, 67% in peripheral neuropathy, 62% in FBSS, and 62% in phantom limb pain.
  - Similar analyses have indicated that spinal cord stimulation is beneficial for refractory angina being effective in 80% of patients for 1 year and in 57% of patients for up to 5 years [24, 25].
  - Studies have reported moderately high successful outcome rates for the treatment of CRPS when evaluated within 3 years of implantation (about 60–70%), although there is some discrepancy when evaluating long-term outcomes [26–29].
- A pivotal RCT (15) has shown that paresthesia-free hgih frequency (HF) SCS is significantly superior to conventional SCS. At one-year follow-up, the back pain responder rate for HF was 78.7% (vs. 51.3% for conventional SCS), which was sustained for an additional one year (76.6% vs. 49.3%). Similar results were obtained for leg pain responder rates.
- Better level of evidence exists for treatment of pain related to FBSS [13–15, 30–37] and CRPS [3, 26, 32–34, 38–42].
- Evidence also exists for treatment of diabetic neuropathies [3, 43–47], abdominal and pelvic pain [3, 48–51], and ischemic pain syndrome [52–54].

Rationale

- SCS was founded on the principles of gate control theory [7]. However, a full understanding of the mechanism of action is still unknown [2].
- Gate control theory suggests that analgesia is obtained by stimulating large A-β fibers in the cord. This action closes the "gate" to incoming nociceptive input from a peripheral source which is being transmitted through small diameter A-δ and C-fibers.
  - The stimulation of A-β fibers is responsible for paresthesias experienced by patients during stimulation at conventional frequency (50 Hz).
- It is also hypothesized that SCS modulates sympathetic nervous system function by inhibiting the hyperexcitability of wide dynamic range (WDR) neurons in the dorsal horn [55].
  - This modulation process involves various neurotransmitter and neuromodulators such as glutamate, γ-amino butyric acid (GABA), adenosine, serotonin, and norepinephrine.
- Gate control theory, however, does not account for the transitioning from an acute pain state to a chronic pain state. This change seems to be associated with the sensitization of the neural networks involved in afferent transmission which is mediated by the overexpression of some synaptic receptors.
- Central sensitization has been recently invoked as a general mechanism for neuropathic chronic pain. This is a manifestation of long-lasting synaptic plasticity which is triggered by nociception input into the dorsal horn.
  - Central sensitization provides a mechanism for pain amplification and reduction of threshold [18].

Table 44.1 Evidence of therapeutic effectiveness of spinal cord stimulation

	Evidence	Systematic reviews/guidelines	Therapeutic studies
Failed back surgery syndrome (FBSS)	Level II	Taylor et al. [30] Grider et al. [31] Turner et al. [32] Bala et al. [33] Dworkin et al. [34] Manchikanti et al. [35]	Kumar et al. [36] North et al. [37] Al-Kaisy et al. [13] Van Buyten et al. [14] Kapural et al. [15]
Complex regional pain syndromes (CRPS)	Level II	Taylor et al. [26] Deer et al. [3] Turner et al. [32] Dworkin et al. [34] North et al. [38] Simpson et al. [39]	Kumar and Rizvi [40] Kemler et al. [41] Moriyama et al. [42]
Diabetic neuropathy	Level IV	Pluijms et al. [43] Deer et al. [3]	Tesfaye et al. [44] Daousi et al. [45] De Vos et al. [46] Kumar et al. [47]
Abdominal/pelvic pain	Level IV	Deer et al. [3]	Tiede et al. [48] Khan et al. [49] Kapural et al. [50, 51]
Ischemic pain syndrome	Level IV	Ubbink et al. [52] Ubbink and Vermeulen [53]	Amann et al. [54]

  - Central sensitization involves changes in both pre- and postsynaptic interactions, including calcium levels in the postsynaptic process.
- Nerve injury may induce genetic changes in the nerve cells which regulate the expression of neuropeptides, cytokines, and other agents that trigger and maintain neuropathic chronic pain.
- Glial cells may also play an important role in the mechanism of central sensitization as nerve injury initiates glial activation and immune system response [56].
- Supraspinal mechanisms have also been proposed to explain SCS action [2]. These involve descending mechanisms mediated by endogenous opioids and serotonin-based systems.
- Given that the mechanism of the establishment and maintenance of neuropathic pain is not well established, it is also unclear how SCS can relieve pain.
- It has even being suggested that the mechanism of action may vary depending on various factors, such as etiology and pathology, segmental location of the stimulating electrode, and factors related to vasculature [57].
- The introduction and proven efficacy of high-frequency stimulation and burst stimulation will encourage research on the mechanisms of action. Studies suggest that these forms of stimulation have modes of actions that differ from that provided by conventional SCS [16, 58, 59].

Indications

Indications for spinal cord stimulation are generally based on the type of pain and location. These are as follows:

- Axial back pain indications
  - FBSS
  - Failed neck surgery
  - Whiplash injury
  - Other chronically painful back conditions
- Radicular pain radiating to either upper or lower limbs
- Neuropathic pain
  - Postherpetic neuralgia (PHN)
  - Phantom pain
  - Other neuropathic pain conditions (arachnoiditis, post-traumatic neuralgias)
- CRPS
- Visceral pain
  - Intractable and refractory angina
  - Post-thoracotomy syndrome (PTS)
  - Chronic painful urogenital conditions
  - Refractory mesenteric ischemia
- Peripheral vascular disease (PVD)
  - Nonoperable PVD/limb ischemia

Anatomy

- The epidural space extends from the foramen magnum to the sacrococcygeal membrane and contains loose areolar tissue, fat, and the vertebral venous plexus.
  - The epidural space lies between the ligamentum flavum and the dura mater.
  - The ligamentum flavum is relatively thin in the cervical region and becomes thicker as it extends caudally [60]. The distance between the ligamentum flavum and the dura is the smallest above C6 being only 1.5–2 mm. Cervical flexion may widen the space up to 3–4 mm [61]. The space is the greatest at the L2 level, measuring 5–6 mm in adults. In the thoracic spine, the epidural space is 3–4 mm wide.
- The spinal cord is a vital constituent of the central nervous system which extends from the foramen magnum where it is continuous with the medulla to the L1 or L2 level of the vertebral column.
  - The spinal cord is composed of white and gray matter uniformly organized and divided into four regions: cervical, thoracic, lumbar, and sacral. Each region is comprised of several segments.
  - Two consecutive rows of nerve roots emerge on each of the sides of the spinal cord.
  - The nerve roots form 31 pairs of spinal nerves, which contain motor and sensory nerve fibers to and from all parts of the body.
  - In each spinal segment, there are dorsal roots entering and ventral roots exiting the cord.
    - Ventral roots are composed of motor nerve fibers that allow for skeletal muscle control.
    - Dorsal roots are composed of sensory nerve fibers. Each dorsal root has a ganglion (DRG) in which the cell bodies of sensory neurons are located.
  - Each dorsal spinal cord segment innervates a dermatome. Dermatomes are areas of the skin which are innervated by peripheral fibers that originate from a single DRG.
    - Dermatomes can be mapped on the body surface and allow for accurate localization of pain sensation to a particular dorsal root ganglion or spinal cord segment.
- Transversal sectioning of the spinal cord reveals white matter in the periphery surrounding areas of gray matter (Fig. 44.1).
  - Gray matter contains neuronal cell bodies and glial cells and is divided into four areas: the dorsal horn, the ventral horn, the intermediate column, and the lateral horn.

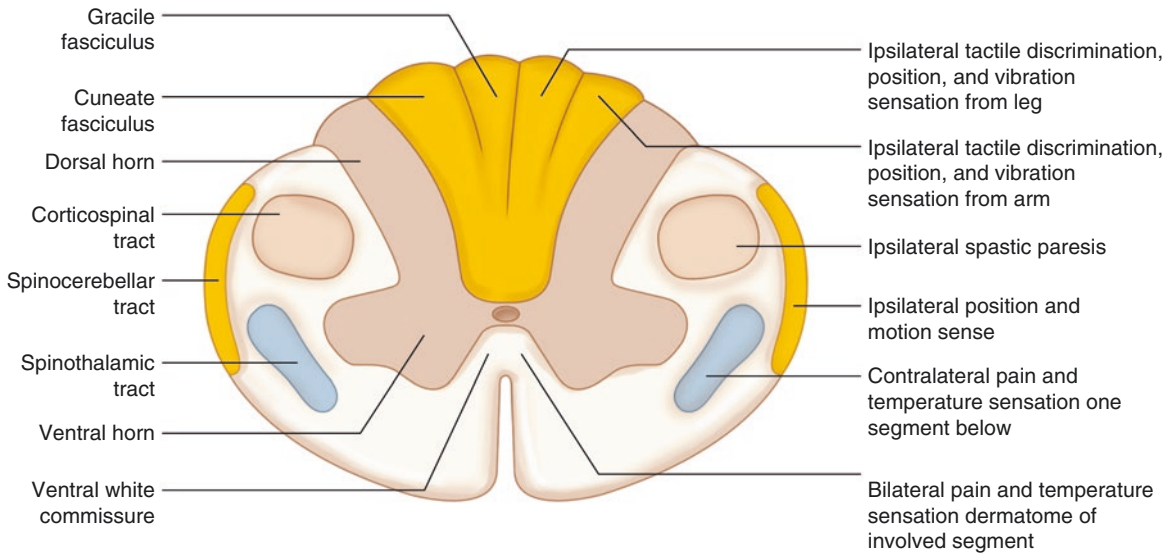

Fig. 44.1 Transverse section of the spinal cord

- The dorsal horn is made up of sensory nuclei which process somatosensory information in ascending way to the midbrain and diencephalon.

– White matter is composed of glial cells and myelinated and unmyelinated fibers, which conduct signals in both ascending and descending direction. White matter is divided into the dorsal column (or funiculus), the lateral column, and the ventral column.
– Ascending tracts are found in all columns, while descending ones are only found in the lateral and ventral columns.
– Ascending tracts emerge from primary neurons located in the DRG.
  - The gracile and cuneate fasciculi occupy the dorsal column (Fig. 44.1). Fibers in these tracts carry tactile, pressure, vibration, and propriosensory information to the brain.
  - The spinothalamic tract carries pain, temperature, and touch information from somatic and visceral structures.
  - The spinocerebellar tract carries unconscious proprioception information.
– Descending tracts originate from various cortical areas in the brain and from the brain stem nuclei.
  - The corticospinal and rubrospinal tracts carry voluntary motion information.
  - The reticulospinal and vestibulospinal tracts mediate balance and postural movements.
  - The Lissauer's tract carries information to the dorsolateral funiculus (DLF), which regulates incoming pain sensation at the spinal level.

Technical Aspects

- The thickness of the dorsal cerebrospinal fluid (dCSF) layer varies according to the spinal level.
  – At the T6 level, the thickness may vary between 4 and 8 mm, while in the mid-cervical spine may be as small as 1.5–4 mm [62].
  – The thicker dCSF layer in the mid-thoracic spine results in higher paresthesia threshold requiring higher stimulation current.
  – The threshold for dorsal root fibers is lower than the one for dorsal column fibers in the mid-thoracic spine [63]. This implies that the stimulating current must be directed along the axis of the electrode to avoid stimulation of the dorsal root fibers which may cause unpleasant paresthesias in the trunk.
  – This is achieved by positioning the stimulating lead at or very close to the midline. The sensory fibers of the dorsal column are segmentally aligned along a mediolateral direction with the caudal body regions grouped toward the midline and the more proximal structures located laterally (Fig. 44.2).
- The number of leads and contact electrodes per lead depends on the painful areas (dermatomes) to be covered.
- Commercially available leads contain 4, 8, 16, or 32 electrodes that can be arranged in either a cylindrical or a paddle lead.
  – Implantation of permanent paddle leads requires a laminectomy or laminotomy, while cylindrical leads are implanted percutaneously.

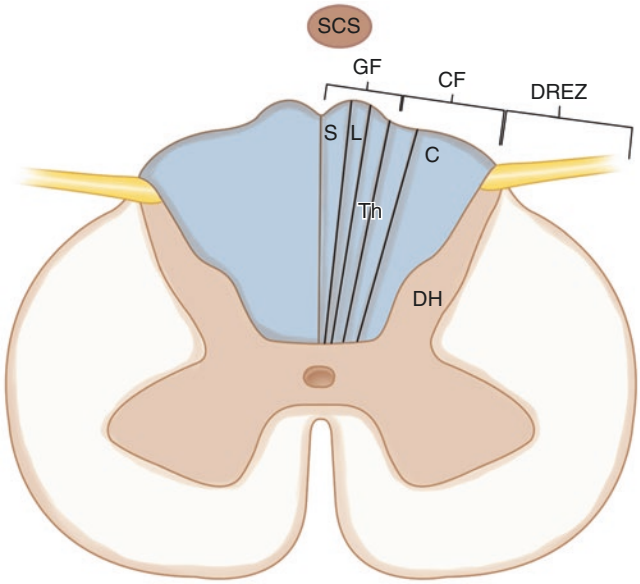

Fig. 44.2 Important anatomical features of the dorsal column relevant to spinal cord stimulation. The stimulator (SCS) is placed in the anatomical dorsal midline. Sensory structures of the dorsal cord (DC) are segmentally aligned in mediolateral direction with caudal body regions grouped toward the midline, while more proximal structures are represented laterally in the dorsal columns. *DREZ* dorsal root entry zone, *GF* gracile fasciculus, *FC* cuneate fasciculus, *DH* dorsal horn, *S* sacral, *L* lumbar, *Th* thoracic, *C* cervical fibers

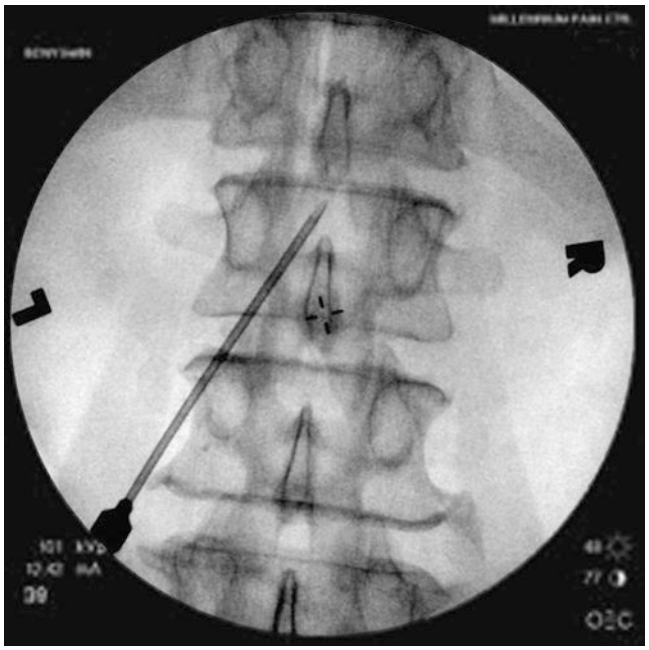

Fig. 44.3 Paramedian fashion needle approach of the epidural space

  - A large number of electrodes allows for a larger number of polarity combinations, including the relocation of the cathode to a position that better matches the painful area.
  - A narrow electrode to electrode distance and a large number of electrodes allow for extended coverage of the electrical field along the axis of the lead.
  - A larger number of electrodes per lead may also allow for easier reprogramming of the stimulator to cover painful region(s) in cases involving lead migration. This prevents revision of the system.
- The number of leads to be implanted depends on the total area to be covered. One lead is enough for covering an ipsilateral area as is the case for some CRPS, mononeuropathy, post-thoracotomy syndrome, postherpetic neuralgia, etc.
  - In cases when pain is bilateral or extends into a large bodily region, the implantation of two or three leads may be required.
    - Patients with predominantly axial low back pain who are not able to tolerate paresthesias in the trunk or lower extremities are candidates for multilead implantation.
    - Two leads aligned parallel (Fig. 44.3) or staggered a couple of millimeters lateral to the midline provide an electrical field that covers the fibers originating in the lower back [64].
    - When the back area cannot be covered with a two-lead arrangement, a tripolar lead arrangement (a transverse tripole) may be used. This uses an eight-electrode lead which is placed in the midline and set as a cathode and four-electrode leads, one at each side, which are set as anodes [65].
- Electrodes in paddle leads have different geometry than in cylindrical leads, which implies that electrical field direction and therefore efficacy should differ.
  - A head-to-head trial that compared the two lead geometries indicates that paddle-style leads do not yield any better clinical outcome relative to percutaneously placed cylindrical leads at 3-year post-procedure [66].
  - Adverse events such as lead fracture and hardware failure that requires revision are more common when paddle leads are surgically implanted [27] (Table 44.2).
- Current delivered by the device determines the intensity of the electrical field applied to the spinal cord.
- Available SCS systems utilize either constant current or constant voltage outputs.
  - Constant current devices may be advantageous over constant voltage devices because the electric field supplied by constant current device does not depend on impedance variations.
    - The development of scar tissue around the implanted lead will cause an increase in lead impedance. For a current voltage device, this implies that current will drop, thus decreasing the intensity of the electric field.

Table 44.2 A comparison of surgical paddle and percutaneous leads

Percutaneous	Surgical paddle
Omnidirectional stimulation field	Unidirectional stimulation field
Large battery consumption (more frequent recharging)	Small battery consumption (less frequent recharging)
Mobile	Fixed
Minimally invasive	Requires laminectomy
Easier to revise	Harder to revise
Easier to add	Requires more revision

Table 44.3 Pain target and lead location

Location of pain	Lead entry level	Final level of lead tip
Upper limb	T4–T6	C3–C5
Upper chest wall	T6–T8	T1–T2
Hip, back, and leg	T12, L1, or L2	T7–T8 or T9
Leg	L1 or L2	T9–T10
Foot	L2 or L3	T11–L1

The Spinal Cord Stimulator Trial

- SCS therapy is tested during a preimplantation trial period.
- A trial period is used to determine if a patient will respond to treatment. During the trial period, both the level of pain relief and changes in quality of life are documented. During this time, patients are encouraged to perform activities of daily life (ADL), without compromising the implantation procedure, to ensure that improvements observed during the trial are associated with SCS.
- Trials are performed as outpatient procedures and require a pretrial psychological evaluation in order to assess if there are psychological factors that might interfere with SCS therapy.
- There are two options available for placing the stimulator leads in the epidural space, which option is chosen depends on individual preference.
  - A trial lead can be placed percutaneously using an epidural needle. The lead is then secured to the skin. This procedure can be performed in an outpatient manner in a sterile clinical setting at the interventionalist site.
  - Alternatively, an incision can be made to secure the lead to spinal ligaments in a "permanent" fashion. This procedure must be performed in an operating room (OR) within a hospital setting, which may increase cost.
    - The main advantage of the "permanent" trial is that if the trial is successful, then the implanted trial lead(s) may be kept in place. Thus, intervention only requires tunneling of lead(s) and its connection to the implantable pulse generator (IPG).
    - If the trial is not successful, the lead(s) must be removed surgically; thus the patient may be subjected to additional expenses and unnecessary scarring.
- Percutaneous implantation of trial leads does not require surgical interventions for unsuccessful trials. It also provides better reliability on evaluating the SCS because it avoids the effect of the potentially confounding pain from the incision [67].
- Trial periods last between 3 and 10 days.
- Trial uses a programmable external pulse generator (EPG) which operates on alkaline batteries and is secured to the patient via a carrying belt.
- Permanent implantation of an SCS device requires at least a recorded 50% pain relief [68] and improvement in quality of life. However, some authors consider that a 30% reduction in pain is as clinically significant as 50% [69, 70].
- The interventionalist should be careful when evaluating efficacy during the trial period because this lasts only a few days and there is the possibility of significant placebo effect ("honeymoon" effect).
  - In addition to pain scores and quality of life scores, other evaluations of physical and psychological outcomes may be used to provide a better assessment of the success or failure of the SCS trial.

Lead Placement Technique

- The majority of trial leads are placed percutaneously.
- Prophylactic antibiotics are administered before the procedure to reduce the risk of infections.
- The skin around and over the entry region is prepared, wiped, and draped using aseptic techniques.
  - Sterile technique, including mask and gown, must be implemented during the procedure.
- For thoracic and lumbar placement of the lead, the patient is placed in prone position with a pillow underneath the abdomen in order to decrease lumbar lordosis.
  - In the case of cervical lead placement, the pillow is placed underneath the chest to increase cervical flexion.
- Fluoroscopic aid is used to visualize the pedicles of the vertebral bodies.
- The entry point, which is one or two levels below the desired epidural level (Table 44.3), is marked using a paramedian approach (Fig. 44.3). This approach allows for a more acute angle of entry, which facilitates lead advancement.
  - If two leads are going to be implanted, the pedicles are marked at two consecutive levels or on the contralateral side.
- Lidocaine (1%) is applied to induce skin and subcutaneous analgesia, and then a 14- or 15-gauge epidural access needle is used to identify the epidural space by using the

loss of resistance technique while viewing using fluoroscopic imaging.
- Once the epidural space is identified, the SCS lead is advanced through the needle into the dorsal epidural space under fluoroscopic guidance. The lead is advanced slowly as to maintain the position of the lead at the midline or in the desired ipsilateral side for patients with unilateral pain.
  - It is important to keep the lead in the midline (Fig. 44.4) or only a few millimeters away from the midline to prevent the advancement of the lead in the anterior epidural space.
- Once the lead is correctly positioned in the dorsal epidural space (Fig. 44.5) and with the patient awake, the stimulator is programmed.
  - Programming must successfully cover the painful areas by using sensory stimulation and paresthesia feedback from the patient.
- Once programming is successfully achieved, the needle is carefully removed while keeping the lead in position. This is best achieved under live fluoroscopy imaging.
- The lead(s) is(are) secured to the skin by using sutures or Steri-Strips™ and then covered with Tegaderm™ dressing.
- The leads are connected to the EPG and the patient is discharged home after the appropriate coverage is achieved.
  - The patient must be instructed on the proper operation of the remote unit that controls the EPG.
  - The patient must be instructed to contact the physician's office in any case of loss of paresthetic coverage, fever, severe low back pain, limb weakness, or loss of bowel or bladder control.
- During a permanent SCS implantation, the percutaneous leads or paddle lead (which requires a small laminotomy) is placed at the same level as was determined during trial.
- For a percutaneous permanent implantation, the trial leads are removed and permanent implants are placed as was done during the trial implantation.
  - Following the correct lead placement and confirmation of coverage of painful areas, an incision is made around the needle.
  - Tissues around the needle are dissected until exposing the supraspinous ligament. At this point, an anchor device is used to secure the lead to the supraspinous ligament.
  - A paddle lead can also be secured to the spine in a similar fashion.
- A subcutaneous pocket is created in the buttock area for the IPG.
- A tunneling device is used to advance the lead in the subcutaneous tissue to the pocket, and then the lead is connected to the IPG.
- The incision is sutured or stapled and the patient discharged after the stimulator has been tested and the

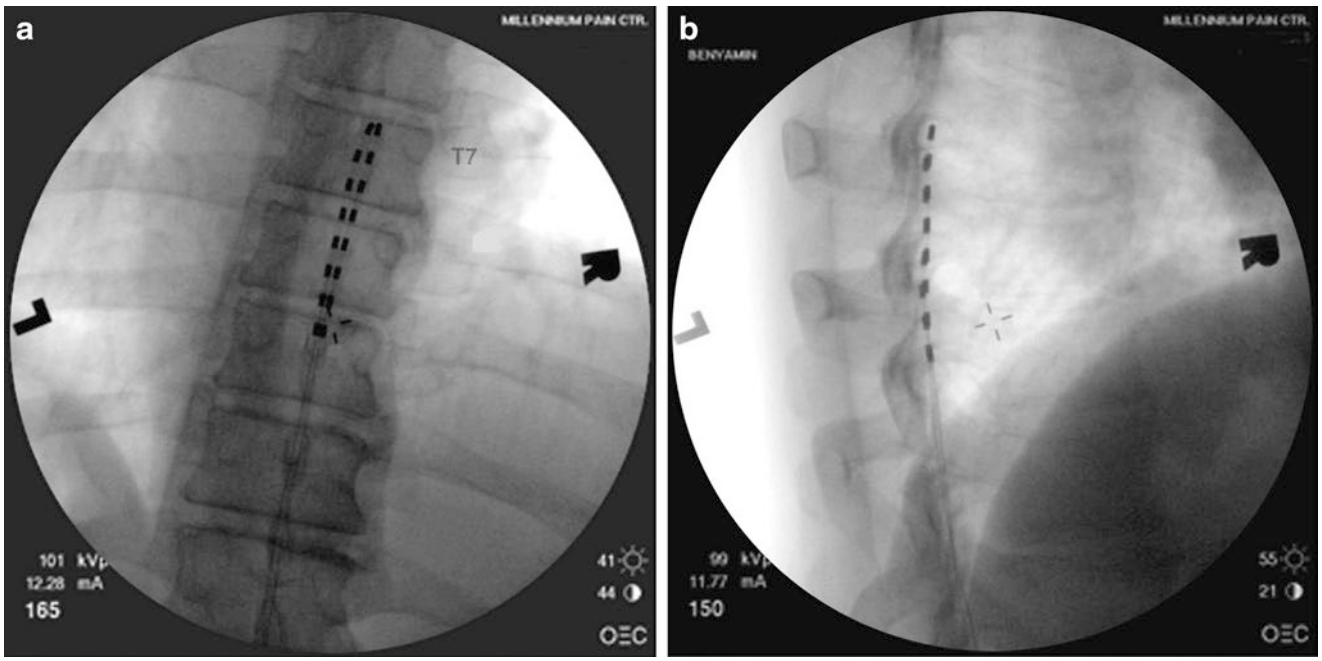

Fig. 44.4 Fluoroscopic image of dual cylindrical eight-contact leads placed in the cervical epidural space. Notice the midline placement and parallel alignment of the two leads allowing for multiple polar arrangements

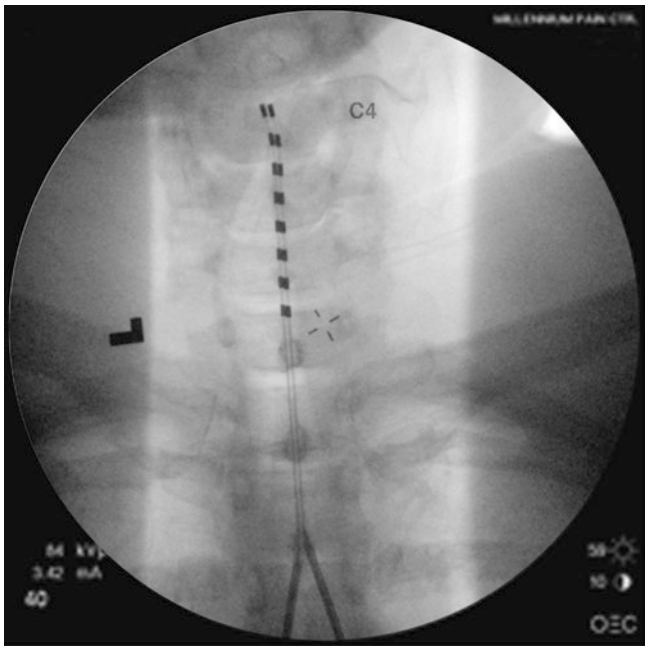

Fig. 44.5 Fluoroscopic images showing dual eight-contact leads placed in the thoracic epidural space. (**a**) Anteroposterior view showing midline position and parallel alignment of leads. (**b**) Lateral view showing the position of the leads in the dorsal epidural space

patient has been trained to program the IPG using the remote control.
- Sutures/staples are usually removed 7–10 days later.

Side Effects and Complications

- Overall up to 34% of SCS patients may experience an adverse event [32].
- Lead migration is the most common complication. Incidence is not well established, but typically an average of 17% of SCS implantations involve lead migration.
  - Lead migration may require revision or explantation.
  - Cylindrical leads most often migrate caudally.
  - In case of minor lead migration, multicontact leads and multiple polarity arrangements allow for reprogramming and recapturing of paresthesia coverage.
  - Silicone adhesive may be used to further secure the lead to anchors, thus reducing the risk of lead migration [71].
- Lead fracture is also a common complication, with about 7% occurrence rate.
- Infection at the incision site of lead or in the surgical IPG pocket [5, 27, 72].
  - Severe infection may warrant explantation of the lead and IPG in rare instances.
  - Some swelling and redness around the incision site is normal, but it should not persist for more than 5–7 days following implantation.
  - The continued worsening of a fever and increased pain around the implantation pocket are possible signs of an ongoing infection.
  - Implantation of spinal cord stimulation systems is not recommended in patients prone to infection or coagulation disorders.
- Battery and IPG failures are also potential complications, although their occurrence rates are relatively low. Technological advances have made devices more reliable.
- Some SCS systems are not compatible with magnetic resonance imaging (MRI) techniques.
  - The benefit of SCS implantation must be weighed against the risk of depriving a patient from obtaining MRIs in the future.
  - Some devices are compatible with MRI equipment under certain circumstances.
- Interactions of the SCS device with other devices outside the body have also been reported. Manufacturers provide caution notes in the device packaging and information.
- Other adverse events previously noted in case reports and with very low occurrence include epidural fibrosis, epidural hematoma, dural puncture, IPG seroma, and suspected nerve, or spinal cord injury [73].

Precautions

- Prescribing antibiotics prophylactically may help to reduce the risk of infection.
- A psychological evaluation is important. The cognitive level of the patient must be sufficient enough to understand certain responsibilities and expectations that are tied to the permanent implantation and further management of the device (i.e., charging the device, adjusting stimulation amplitude, self-management of paresthesia, and pain).
- Proper training of the clinician is of outmost importance. SCS involves surgical intervention that requires placing a lead into the epidural space. Improper surgical technique may cause devastating adverse events.
- Proper lead anchoring and tunneling are required to reduce the incidence of lead migration or fracture.
- It is important to test the signal generator and all connections to the lead, particularly at the time of permanent implantation.
- Consider the amount of epidural space available before proceeding with implantation. In some cases in which patients have spinal canal stenosis, it may be prudent to have imaging diagnostics (MRI, CT myelogram) of the spinal canal diameter.

  - Decompression of spinal canal stenosis may be required before proceeding with implantation of stimulating leads.
- Given that the risk of infection is elevated under certain specific comorbidities, it is important to evaluate the status of the patient before considering SCS.
  - Risk of infection is elevated by immunosuppressive conditions such as HIV.
  - Risk of infection is elevated by immunosuppressive therapies such as the use of steroids.
  - Risk of infection is elevated during extended hospital stays, blood transfusions, inappropriate ventilation, and sterility of the intervention suite.
  - Risk of infection is elevated in patients with diabetes, rheumatoid arthritis, obesity, and/or use of alcohol and tobacco.
  - The use of antibiotics should be considered according to infectious disease standards and on the basis of the prevalent infections and patient's allergic response to antibiotics.
- The implantation of a spinal cord stimulator, although a minimally invasive procedure, requires strict surgical precautions.
  - Restricted traffic in operating room
  - Appropriate use of sterile handling
  - Administration of preoperative antibiotics and previous verification that patient is not allergic to the antibiotics
- Clinician must account for the use of anticoagulant therapy before proceeding with trialing.
  - Guidelines from the American Society of Interventional Pain Physicians (ASIPP), American Society of Regional Anesthesia (ASRA), and European Society of Anesthesiology for management of patients receiving anticoagulation therapy should be followed [35, 74–77].
    - The risk associated with the discontinuation of anticoagulant therapy is well established. The benefits associated with implantation of a spinal cord stimulator must be accounted for in relation to the risk of thromboembolic phenomena.
- Clinician must also account for the benefits associated with SCS and the risk accompanying future restriction to MRI procedures.
- The patient must be educated about procedures, as well as the expectations for SCS and possible risks associated with the implantation. It is equally important to emphasize proper postoperative care (bathing, medications, discharge instructions, etc.).

Key Points

1. Spinal cord stimulation is a minimally invasive treatment that is advantageous in the management of many chronic pain conditions.
2. Spinal cord stimulation requires a trial period before permanent implantation of the stimulating lead and pulse generator. The trial period provides the clinician with valuable information regarding therapeutic efficacy and safety.
3. There is no clear understanding on how spinal cord stimulation provides pain relief, particularly in the context of comparing various modalities (conventional frequency, high frequency, and burst stimulation).
4. There is strong evidence that SCS is effective for failed back surgery syndrome, radiculopathies, and complex regional pain syndromes.
5. SCS therapy is more effective when used early in the progress of the establishment of a chronic pain condition.
6. Common complications of SCS are associated with migration or fracture of the lead(s) and infection at the implantation site.
7. Advancements in technology including miniaturization of the pulse generator, improved battery performance, optimized lead, and software design have made SCS therapy a viable alternative to more invasive procedures.
8. SCS keeps evolving as clinicians, researchers, and device developers continue to understand the effects of stimulation parameters (frequency, amplitude, waveforms) on clinical outcomes. It is expected that RCTs will be conducted to provide proper evidence of the efficacy and safety of available SCS modalities on various chronic pain conditions.

Acknowledgments This book chapter is modified and updated from a previous book chapter, "Spinal Cord Stimulation" by Ricardo Vallejo, MD, PhD; Ramsin M. Benyamin, MD; Jeffery Kramer, PhD; and Donny Bounds, MSN, in *Interventional Techniques in Chronic Spinal Pain* published by ASIPP Publishing. Permission has been obtained from ASIPP Publishing.

References

1. Smits H, van Kleef M, Holsheimer J, et al. Experimental spinal cord stimulation and neuropathic pain: mechanism of action, technical aspects, and effectiveness. Pain Pract. 2013;13:154–68.
2. Zhang TC, Janik JJ, Grill WM. Mechanisms and models of spinal cord stimulation for the treatment of neuropathic pain. Brain Res. 2014;1569:19–31.
3. Deer TR, Mekhail N, Provenzano D, et al. The appropriate use of neurostimulation of the spinal cord and peripheral nervous system for the treatment of chronic pain and ischemic diseases: the neuromodulation appropriateness consensus committee. Neuromodulation. 2014;17:515–50.
4. Boswell MV, Trescot AM, Datta S, et al. Interventional techniques: evidence-based practice guidelines in the management of chronic spinal pain. Pain Physician. 2007;10:7–111.
5. Cameron T. Safety and efficacy of spinal cord stimulation for the treatment of chronic pain: a 20-year literature review. J Neurosurg. 2004;100:254–67.
6. Bullock TD, Hopkins CD, Popper AN, et al. Electroreception. New York: Springer Science+Business Media; 2005.

7. Gensel L. The medical world of Benjamin Franklin. J Royal Soc Med. 2005;98:534–8.
8. Melzack R, Wall PD. Pain mechanisms: a new theory. Science. 1965;150:971–9.
9. Shealy CN, Taslitz N, Mortimer JT, et al. Electrical inhibition of pain: experimental evaluation. Anesth Analg. 1967;46:299-305.
10. Shealy CN, Mortimer JT, Reswick JB. Electrical inhibition of pain by stimulation of the dorsal columns: preliminary clinical report. Anesth Analg. 1967;46:489-491.
11. Gildenberg PL. History of electrical neuromodulation for chronic pain. Pain Med. 2006;7:S7–S13.
12. Kumar K, Rizvi S. Historical and present state of neuromodulation in chronic pain. Curr Pain Headache Rep. 2014;18:387.
13. Al-Kaisy A, Van Buyten JP, Smet I, et al. Sustained effectiveness of 10 kHz high-frequency spinal cord stimulation for patients with chronic, low back pain: 24-month results of a prospective multicenter study. Pain Med. 2014;15:347–54.
14. Van Buyten JP, Al-Kaisy A, Smet I, et al. High-frequency spinal cord stimulation for the treatment of chronic back pain patients: results of a prospective multicenter European clinical study. Neuromodulation. 2013;16:59–65.
15. Kapural L, Cong Y, Doust MW, et al. Comparison or 10-kHz high-frequency and traditional low-frequency spinal cord stimulation for the treatment of chronic back and leg pain: 24-month results from a multicenter, randomized, controlled pivotal trial. Neurosurgery 2016; 79:667–677.
16. De Ridder D, Vanneste S, Plazier M, et al. Burst spinal cord stimulation: toward paresthesia-free pain suppression. Neurosurgery. 2010;66:986–90.
17. Jensen TS, Baron R, Haanpää M, et al. A new definition of neuropathic pain. Pain. 2011;152:2204–5.
18. von Hehn CA, Baron R, Woolf CJ. Deconstructing the neuropathic pain phenotype to reveal neural mechanisms. Neuron. 2012;73:638–52.
19. Wu G, Ringkamp M, Murinson BB, et al. Degeneration of myelinated efferent fibers induces spontaneous activity in uninjured C-fiber afferents. J Neurosci. 2002;22:7746–53.
20. Janssen SP, Truin M, Van Kleef M, et al. Differential GABAergic disinhibition during the development of painful peripheral neuropathy. Neuroscience. 2011;184:183–94.
21. Scholz J, Broom DC, Youn DH, et al. Blocking caspase activity prevents transsynaptic neuronal apoptosis and the loss of inhibition in lamina II of the dorsal horn after peripheral nerve injury. J Neurosci. 2005;25:7317–23.
22. Coull JA, Beggs S, Boudreau D, et al. BDNF from microglia causes the shift in neuronal anion gradient underlying neuropathic pain. Nature. 2005;438:1017–21.
23. Ben Achour S, Pascual O. Glia: the many ways to modulate synaptic plasticity. Neurochem Int. 2010;57:440–5.
24. Bagger JP, Jensen BS, Johannsen G. Long-term outcome of spinal cord electrical stimulation in patients with refractory chest pain. Clin Cardiol. 1998;21:286–8.
25. DeJongste MJ. Efficacy, safety and mechanisms of spinal cord stimulation used as an additional therapy for patients suffering from chronic refractory angina pectoris. Neuromodulation. 1999;2:188–92.
26. Taylor RS, Van Buyten JP, Buchser E. Spinal cord stimulation for complex regional pain syndrome: a systematic review of the clinical and cost-effectiveness literature and assessment of prognostic factors. Eur J Pain. 2006;10:91–101.
27. Kumar K, Hunter G, Demeria D. Spinal cord stimulation in treatment of chronic benign pain: challenges in treatment planning and present status, a 22-year experience. Neurosurgery. 2006;58:481–96.
28. Kemler MA, De Vet HC, Barendse GA, et al. The effect of spinal cord stimulation in patients with chronic reflex sympathetic dystrophy: two years' follow-up of the randomized controlled trial. Ann Neurol. 2004;55:13–8.
29. Kemler MA, de Vet HC, Barendse GA, et al. Spinal cord stimulation for chronic reflex sympathetic dystrophy--five-year follow-up. N Engl J Med. 2006;354:2394–6.
30. Taylor RS, Desai MJ, Rigoard P, et al. Predictors of pain relief following spinal cord stimulation in chronic back and leg pain and failed back surgery syndrome: a systematic review and meta-regression analysis. Pain Pract. 2014;14:489–505.
31. Grider JS, Manchikanti L, Carayannopoulos A., et al. Effectiveness of Spinal Cord Stimulation in Chronic Spinal Pain: A Systematic Review Pain Physician 2016; 19;E33–E54.
32. Turner JA, Loeser JD, Deyo RA, et al. Spinal cord stimulation for patients with failed back surgery syndrome or complex regional pain syndrome: a systematic review of effectiveness and complications. Pain. 2004;108:137–47.
33. Bala MM, Riemsma RP, Nixon J, et al. Systematic review of the (cost-)effectiveness of spinal cord stimulation for people with failed back surgery syndrome. Clin J Pain. 2008;24:741–56.
34. Dworkin RH, O'Connor AB, Kent J, et al. Interventional management of neuropathic pain: NeuPSIG recommendations. Pain. 2013;154:2249–61.
35. Manchikanti L, Abdi S, Atluri S, et al. An update of comprehensive evidence-based guidelines for interventional techniques in chronic spinal pain. Part II: guidance and recommendations. Pain Physician. 2013;16:S49–283.
36. Kumar K, Taylor RS, Jacques L, et al. The effects of spinal cord stimulation in neuropathic pain are sustained: a 24-month follow-up of the prospective randomized controlled multicenter trial of the effectiveness of spinal cord stimulation. Neurosurgery. 2008;63:762–70.
37. 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;56:98–107.
38. North R, Shipley J, Prager J, et al. Practice parameters for the use of spinal cord stimulation in the treatment of chronic neuropathic pain. Pain Med. 2007;8:S200–75.
39. Simpson EL, Duenas A, Holmes MW, et al. Spinal cord stimulation for chronic pain of neuropathic or ischaemic origin: systematic review and economic evaluation. Health Technol Assess. 2009;13:1–154.
40. Kumar K, Rizvi S. Cost-effectiveness of spinal cord stimulation therapy in management of chronic pain. Pain Med. 2013;14:1631–49.
41. Kemler MA, de Vet HC, Barendse GA, et al. Effect of spinal cord stimulation for chronic complex regional pain syndrome type I: five-year final follow-up of patients in a randomized controlled trial. J Neurosurg. 2008;108:292–8.
42. Moriyama K, Murakawa K, Uno T, et al. A prospective, open-label, multicenter study to assess the efficacy of spinal cord stimulation and identify patients who would benefit. Neuromodulation. 2012;15:7–11.
43. Pluijms WA, Slangen R, Joosten EA, et al. Electrical spinal cord stimulation in painful diabetic polyneuropathy, a systematic review on treatment efficacy and safety. Eur J Pain. 2011;15:783–8.
44. Tesfaye S, Watt J, Benbow SJ, et al. Electrical spinal-cord stimulation for painful diabetic peripheral neuropathy. Lancet. 1996;348:1698–701.
45. Daousi C, Benbow SJ, MacFarlane IA. Electrical spinal cord stimulation in the long-term treatment of chronic painful diabetic neuropathy. Diabet Med. 2005;22:393–8.
46. de Vos CC, Rajan V, Steenbergen W, et al. Effect and safety of spinal cord stimulation for treatment of chronic pain caused by diabetic neuropathy. J Diabetes Complicat. 2009;23:40–5.
47. Kumar K, Toth C, Nath RK. Spinal cord stimulation for chronic pain in peripheral neuropathy. Surg Neurol. 1996;46:363–9.

48. Tiede JM, Ghazi SM, Lamer TJ, et al. The use of spinal cord stimulation in refractory abdominal visceral pain: case reports and literature review. Pain Pract. 2006;6:197–202.
49. Khan YN, Raza SS, Khan EA. Application of spinal cord stimulation for the treatment of abdominal visceral pain syndromes: case reports. Neuromodulation. 2005;8:14–27.
50. Kapural L, Narouze SN, Janicki TI, et al. Spinal cord stimulation is an effective treatment for the chronic intractable visceral pelvic pain. Pain Med. 2006;7:440–3.
51. Kapural L, Nagem H, Tlucek H, et al. Spinal cord stimulation for chronic visceral abdominal pain. Pain Med. 2010;11:347–55.
52. Ubbink DT, Vermeulen H, Spincemaille GH, et al. Systematic review and meta-analysis of controlled trials assessing spinal cord stimulation for inoperable critical leg ischaemia. Br J Surg. 2004;91:948–55.
53. Ubbink DT, Vermeulen H. Spinal cord stimulation for non-reconstructable chronic critical leg ischaemia. Cochrane Database Syst Rev. 2013;2:CD004001.
54. Amann W, Berg P, Gersbach P, et al. Spinal cord stimulation in the treatment of non-reconstructable stable critical leg ischaemia: results of the European Peripheral Vascular Disease Outcome Study (SCS-EPOS). Eur J Vasc Endovasc Surg. 2003;26:280–6.
55. Linderoth B, Foreman RD, Meyerson BA. Mechanisms of action of spinal cord stimulation. In: Lozano AM, Gildenberg PL, Tasker RR, editors. Textbook of stereotactic and functional neurosurgery: McGraw Hill; 2009. p. 2331–48.
56. Calvo M, Bennett DL. The mechanisms of microgliosis and pain following peripheral nerve injury. Exp Neurol. 2012;234:271–82.
57. Linderoth B, Foreman RD. Mechanisms of spinal cord stimulation in painful syndromes: role of animal models. Pain Med. 2006;7:S14–26.
58. Song Z, Viisanen H, Meyerson BA, et al. Efficacy of kilohertz-frequency and conventional spinal cord stimulation in rat models of different pain conditions. Neuromodulation. 2014;17:226–34.
59. Shechter R, Yang F, Xu Q, et al. Conventional and kilohertz-frequency spinal cord stimulation produces intensity- and frequency-dependent inhibition of mechanical hypersensitivity in a rat model of neuropathic pain. Anesthesiology. 2013;119:422–32.
60. Kleinman W. Spinal, epidural, and caudal blocks. In: Morgan GE, Mikhail MS, Murray M, editors. Clinical anesthesiology. 3rd ed. New York: Lange Medical Books/McGraw Hill; 2002. p. 253–82.
61. Raj P, Lou L, Erdine S, et al. Cervical epidural nerve block. In: Radiographic imaging for regional anesthesia and pain management. New York: Churchill Livingstone; 2002. p. 99–105.
62. Alo KM, Holsheimer J. New trends in neuromodulation for the management of neuropathic pain. Neurosurgery. 2002;50:690–703.
63. Holsheimer J, Barolat G. Spinal geometry and paresthesia coverage in spinal cord stimulation. Neuromodulation. 1998;1:129–36.
64. North RB, Kidd DH, Olin J, et al. Spinal cord stimulation for axial low back pain: a prospective, controlled trial comparing dual with single percutaneous electrodes. Spine (Phila Pa 1976). 2005;30:1412–8.
65. Oakley J, Espinosa F, Bothe H, et al. Transverse tripolar spinal cord stimulation: results of an international multicenter study. Neuromodulation. 2006;9:192–203.
66. North RB, Kidd DH, Petrucci L, et al. Spinal cord stimulation electrode design: a prospective, randomized, controlled trial comparing percutaneous with laminectomy electrodes: part II-clinical outcomes. Neurosurgery. 2005;57:990–6.
67. Waldman S. Interventional pain management. 2nd ed. Philadelphia: Saunders; 2001.
68. Kumar K, Taylor RS, Jacques L, et al. Spinal cord stimulation versus conventional medical management for neuropathic pain: a multicentre randomised controlled trial in patients with failed back surgery syndrome. Pain. 2007;132:179–88.
69. Farrar JT, Portenoy RK, Berlin JA, et al. Defining the clinically important difference in pain outcome measures. Pain. 2000;88:287–94.
70. Farrar JT, Young JP Jr, LaMoreaux L, et al. Clinical importance of changes in chronic pain intensity measured on an 11-point numerical pain rating scale. Pain. 2001;94:149–58.
71. Renard VM, North RB. Prevention of percutaneous electrode migration in spinal cord stimulation by a modification of the standard implantation technique. J Neurosurg Spine. 2006;4:300–3.
72. Quigley DG, Arnold J, Eldridge PR, et al. Long-term outcome of spinal cord stimulation and hardware complications. Stereotact Funct Neurosurg. 2003;81:50–6.
73. Deer TR, Mekhail N, Provenzano D, et al. The appropriate use of neurostimulation: avoidance and treatment of complications of neurostimulation therapies for the treatment of chronic pain. Neuromodulation. 2014;17:571–98.
74. Horlocker TT, Wedel DJ, Rowlingson JC, et al. Regional anesthesia in the patient receiving antithrombotic or thrombolytic therapy: American Society of Regional Anesthesia and Pain Medicine evidence-based guidelines (third edition). Reg Anesth Pain Med. 2010;35:64–101.
75. International Spine Intervention Society. Anticoagulants. In: Bogduk N, editor. Practice guidelines for spinal diagnostic and treatment procedures. 2nd ed. San Francisco: International Spine Intervention Society; 2013. p. 9–17.
76. Gogarten W, Vandermeulen E, Van Aken H, et al. European Society of Anaesthesiology. Regional anaesthesia and antithrombotic agents: recommendations of the European Society of Anaesthesiology. Eur J Anaesthesiol. 2010;27:999–1015.
77. Manchikanti L, Malla Y, Wargo BW, et al. A prospective evaluation of bleeding risk of interventional techniques in chronic pain. Pain Physician. 2011;14:317–29.