Evolution of Spinal Cord Surgery for Pain

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The evolution of spinal cord procedures for pain closely followed the evolving understanding of the anatomy and workings of the pain pathways. Clinical observations often led to laboratory studies to define the pain pathways. More knowledge led to more and improved pain procedures. Postoperative observations led to better definition of pain perception. In addition, empirically derived pain procedures sometimes led to increased knowledge of the anatomy and physiology of pain perception.[12]

Spinal cord procedures for pain initially involved interruption of pain pathways and, many years later, the stimulation of the spinal cord in an attempt to inhibit pain transmission. Let us begin by reviewing the historical concept of pain pathways involving the spinal cord (*Fig. 2.1*).

This classical illustration from 1968 by Struppler[54] demonstrates the division of larger fibers, transmitting touch and proprioception, from small C-fibers that transmit pain through peripheral nerves to the spinal cord via the dorsal roots. After synapsing in the dorsal root entry zone, the next order neurons decussate in the anterior commissure to ascend in the contralateral anterolateral quadrant of the spinal cord as the lateral spinothalamic tract. After ascending to the brainstem, the tract sends many fibers to the ventroposterior lateral nucleus of the thalamus, which is associated with perception of sensation, including "pain." The majority of fibers, however, course medially into the reticular formation, medial and intralaminar thalamus, and limbic areas, perhaps where "suffering" is presumably perceived. This illustration shows an often neglected, but poorly demonstrated, pain pathway, the spinoreticular and reticulospinal multisynaptic system that presumably is involved with visceral pain. Not illustrated is Willis' dorsal column visceral pain pathway, which was not discovered until some years after this illustration appeared.

Even before the primary pain pathway was fully appreciated, there was an attempt to control pain by section of peripheral nerves in the 18th century. As one might imagine, except when the pain was produced by injury to the individual nerve, results were not satisfactory. It was demonstrated experimentally by Bell[5] in 1811 and by Magendie[30] in 1822 that incoming sensory information was carried by the dorsal nerve root, and that the ventral root was dedicated to outgoing motor function. However, it was not until 1899 that Abbe[1] performed the first *rhizotomy* or posterior root section in the United States, which was the first spinal surgery for pain. Because it was necessary to perform rhizotomy at a number of levels to treat somatic pain, however, it was rapidly replaced when cordotomy was developed.

The identification of the primary pain pathway as the lateral spinothalamic tract was made after clinical observation of patients who had lost pain sensation after injury to the anterolateral quadrant of the spinal cord. In 1871, Müller[36] observed a patient who had hemisection of the spinal cord with bilateral dorsal column involvement caused by a stab wound, and noted contralateral hemianalgesia, along with bilateral loss of touch sensation. In 1878, Gowers[20] examined a patient who had a discreet injury to the anterolateral quadrant of the cervical spinal cord, caused by a bone spicule driven into the spinal cord after a gunshot wound, and noted discreet contralateral analgesia. This led Spiller[52] to define the spinothalamic pathway in experimental animals in 1905. He noted that the pain sensation entered the dorsal columns supplying the injured area of the body, ascended several levels, and synapsed with the second order neurons, which cross in the anterior commissure to the contralateral spinothalamic tract and ascended to the brainstem. This led Spiller and Martin[53] to perform the first surgical anterolateral *cordotomy* in 1912. The cordotomy procedure was refined by Frazier[11] in 1920. Over the course of the following 51 years, it became the most commonly used and most often successful operation for pain. Throughout that time, numerous technical advances were incorporated to make the resultant analgesia more predictable and to decrease the risk of impaired function. It was noted, however, that chronic pain most often eventually recurred, despite interruption of the known pain pathway, although cancer pain was more often permanently alleviated.[15]

Study of patients with section of the spinothalamic tract led to significant physiological observations. One particularly interesting finding was made in 1943. It is commonly observed that the level of analgesia begins three to five segments below the level of incision into the spinal cord. Hyndman[24] also sectioned Lissauer's tract, which lies at the dorsal root entry zone, at the same level as the lateral spinothalamic

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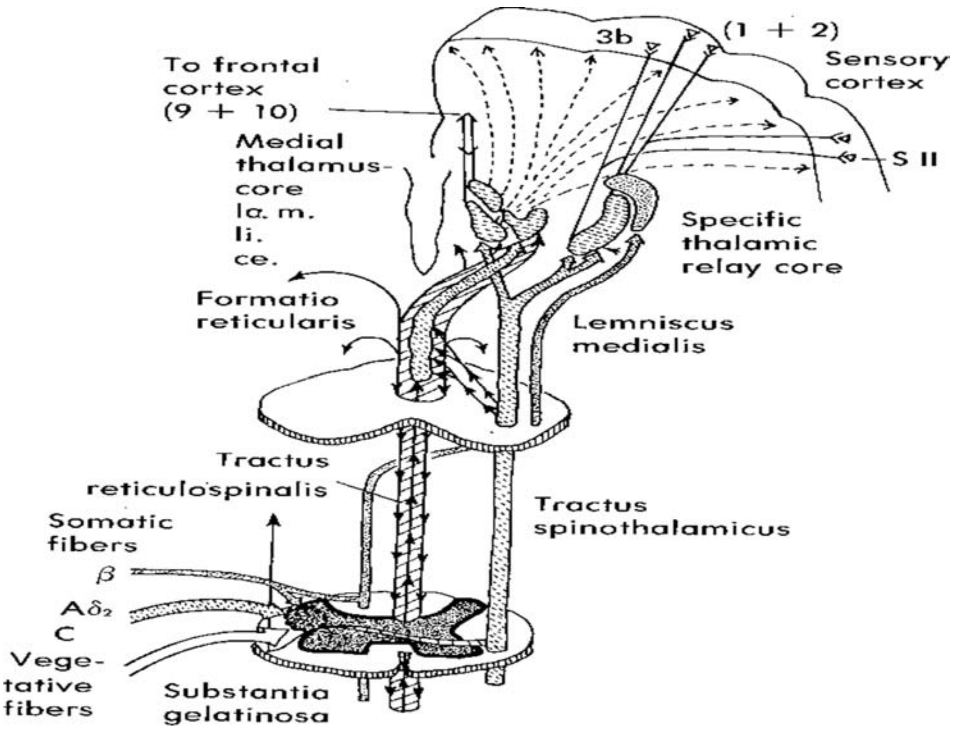

FIGURE 2.1. The pain pathways, showing the small nerve fibers entering the spinal cord via the dorsal root; the decussation and ascent of the lateral spinothalamic tract, which sends some fibers lateral to the thalamus where pain is perceived, but most fibers medially to the medial thalamus and limbic structures that are involved with suffering; and the reticulospinal multisynaptic pathway that reverberates with the spinoreticular pathway. (from, Struppler A: Pathogenesis of clinical pain syndromes. **Langenbecks Arch Chir** 322:552–565, 1968.[54]).

tract and found that after such a lesion the level of analgesia corresponded with the level of spinal cord incision. The conclusion is that the spinothalamic fibers ascend in Lissauer's tract for several segments before crossing over to the contralateral side.

The advantages of lateral spinothalamic cordotomy include good production of analgesia with concomitant immediate relief of pain. The disadvantages include the need to perform laminectomy, often in fragile cancer patients. There is a risk to motor function if the spinal cord incision lies too dorsal, and a risk to bowel and bladder function if it is bilateral.

In addition, corotomy has been disappointing for pelvic, midline, or bilateral lower body pain. In an attempt to treat such pain more effectively, *commissural myelotomy* was introduced. The spinal cord is bisected over those appropriate several segments with the intention of interrupting the decussating spinothalamic fibers conveying the pain. The first report by Armour[3] appeared in 1927. He performed the procedure in only one patient. Despite good pain relief, the patient died of pneumonia postoperatively and Armour did not pursue the procedure. Almost a decade later, Putnam[42] reported on the use of cervical commissural myelotomy for bilateral arm pain by bisecting the spinal cord at several millimeter intervals with a small blade he called a myelotome, which ended in a blunt ball to protect the anterior spinal artery. He and other authors reported a good chance for pain relief (often better than anticipated) that justified the extensive surgery involved, but they noted a risk of at least temporary impairment of lower extremity, bowel, and/or bladder function,[8,51] so myelotomy continued to be used sparingly.

Myelotomy had a rebirth in the 1940s, particularly in France. Wertheimer and Lecuire[58] reported pain relief in more than 100 patients. They, as well as other neurosurgeons performing commissural myelotomy, made a number of observations that defied anatomical logic, although this information was not used until much later. They noted that some patients had widespread analgesia below the incision, even when the myelotomy was restricted to only a few high segments. Interestingly, Dargent[9] reviewed those same patients who had survived 10 years later and concluded that the procedure worked best for visceral and vaginal pain than for somatic or chorionic pain. His associate, Mansuy[32] reported good pain relief even when the incision extended only down to the central grey, not deep enough to interrupt the decussation in the anterior commissure, which at that time did not make anatomical sense. Other authors also reported pain relief extending far beyond the operated segments.[27,51]

In 1946, Pool[41] *sectioned the dorsal columns* in an attempt to treat phantom limb pain, but that procedure never caught on.

Cordotomy continued to be the procedure of choice, and some years later several significant technical advances occurred. In an attempt to achieve the same success as a cordotomy without the need for a laminectomy, Mullan[35]

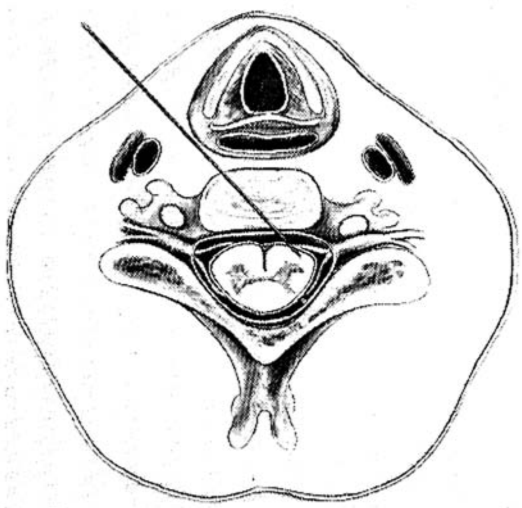

FIGURE 2.2. Lower cervical percutaneous cordotomy, wherein the needle electrode passes diagonally through the disk to the anterolateral spinal cord. (from, Lin PM, Gildenberg PL, Polnkoff PP: An anterior approach to percutaneous lower cervical cordotomy. **J Neurosurg** 25:553–560, 1996.[29]).

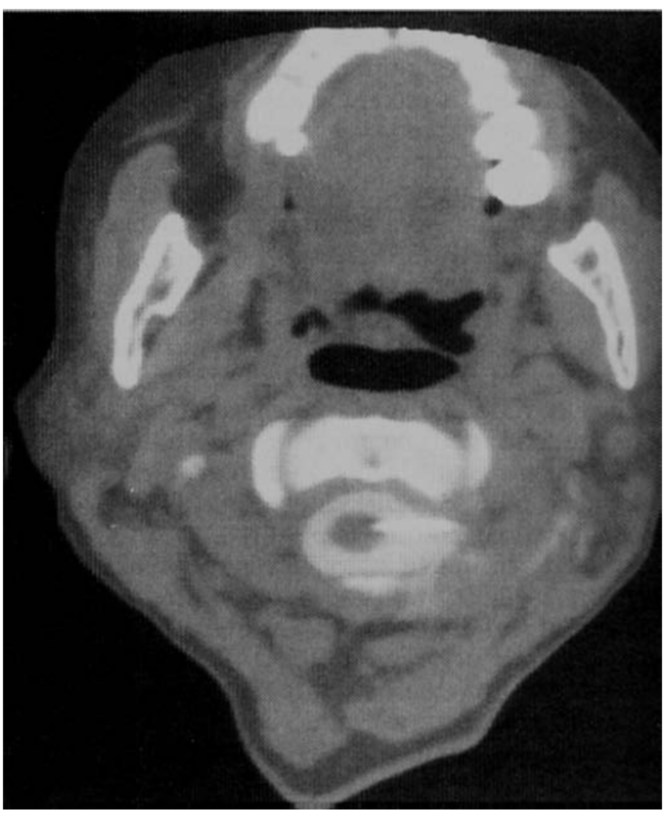

FIGURE 2.3. Percutaneous cervical cordotomy done with computed tomographic guidance that shows the trajectory at the C2 level. (from, Kanpolat Y, Deda H, Akyar S, Caglar S: C.T.-guided pain procedures. **Neurochirurgie** 36:394–398, 1990.[25]).

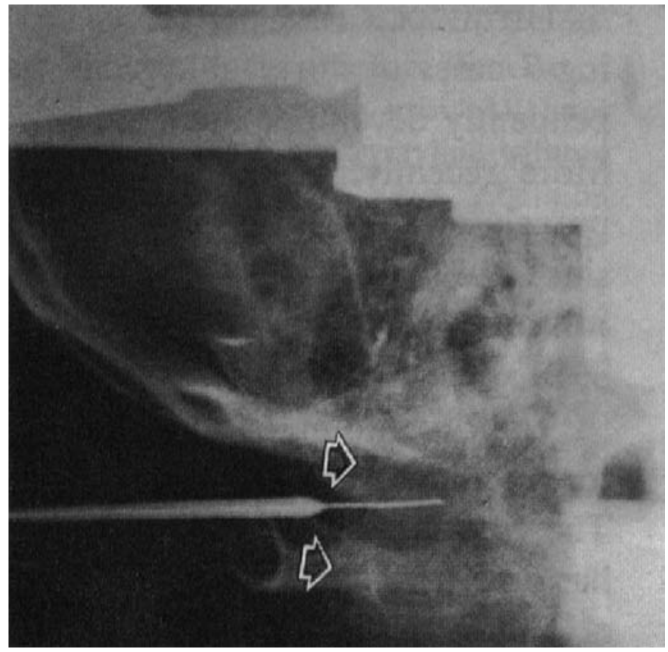

FIGURE 2.4. Hitchcock introduced the electrode from dorsally for percutaneous cervical cordotomy and the for his extralemniscal myelotomy. (from, Hitchcock E: Stereotaxic spinal surgery. A preliminary report. **J Neurosurg** 31:386–392, 1969[22]).

developed an ingenious technique of *percutaneous cervical cordotomy* in 1963. He took advantage of the natural access to the spinal cord by a lateral approach via the crotch between the posterior arch of C1 and the lamina of C2, through which he inserted a radioactive strontium needle. After the needle rested against the anterolateral surface of the cord for a measured time, it was withdrawn. Analgesia and usually pain relief developed gradually thereafter over the subsequent weeks. There were several distinct disadvantages, however. Not every surgeon had access to strontium. With the gradual development of analgesia, it was not possible to tailor the size of the lesion or to stop it if it became too extensive.

This led Rosomoff,[43] a few years later, to use the same approach, but with an electrode that might make a radiofrequency lesion at the desired C2 level target. The patient was awake and could be tested throughout, so the lesion could be adjusted to the patient's needs. However, the procedure held considerable risk when performed bilaterally. In several patients, Rosomoff and his group[28,57] observed Ondine's curse, or sleep induced apnea, a failure of spontaneous respiration, after making the second side lesion. In that condition, the patient is able to breathe when awake, although sometimes experiencing a vague dyspnea. When the patient falls asleep, respiration fails, and the patient may be found dead in bed.[37]

We performed our first bilateral percutaneous C2 cordotomy before Krieger and Rosomoff's[28,57] report of sleep

TABLE 2.1. Historical milestones: Spinal cord procedures for pain

Year	Author (ref. no.)	Procedure
1899	Abbe (1)	Dorsal rhizotomy
1912	Spiller and Martin (52)	Anterolateral cordotomy
1927	Armour (3)	Midline myelotomy
1934	Putnam (42)	Cervical myelotomy
1942	Hyndeman (24)	Lissauer tractotomy
1963	Mullan (34)	Strontium percutaneous cervical cordotomy
1965	Rosomoff (43)	Radiofrequency percutaneous cervical cordotomy
1965	Melzack and Wall	Gate theory
1966	Lin and Gildenberg (29)	Lower cervical percutaneous cordotomy
1966	Sweet and Wepsic (55)	Peripheral nerve stimulation
1967	Shealy (47)	Dorsal column (spinal cord) stimulation
1970	Hitchcock (22)	Extralemniscal myelotomy
1974	Sindou (49)	Dorsal root entry zone incision
1976	Nashold (38)	DREZ radiofrequency procedure
1978	Gildenberg and Hirshberg (17)	Limited myelotomy

induced apnea. The patient had a successful unilateral percutaneous cervical cordotomy, but continued to have pain, now unilateral. After a percutaneous cordotomy on the other side, we observed the patient cautiously over night, and she did well. The day after her second procedure, we felt confident enough to do a percutaneous cordotomy on the second side of another patient. The following day, both patients were on ventilators, both having developed Ondine's curse overnight.

We and Rosomoff approached the problem in two different ways. He and his group developed pulmonary function criteria to select which patients might tolerate the second procedure, and limited bilateral cordotomy to those patients.[28] Paul Lin and I[29] devised a *lower cervical percutaneous cordotomy* approach diagonally through a lower cervical intervertebral disk, so the lesions are made below the emerging respiratory fibers at the C4 level. We reported several techniques to adjust the trajectory of the needle-electrode while it was still adjustable before entering the center of the disk,[18,19] which allowed bilateral percutaneous cervical cordotomy with minimal or no risk to pulmonary function (*Fig. 2.2*).

It seems to be more than coincidence that the two neurosurgeons who published the two largest series of percutaneous cordotomy patients, Hu Rosomoff[44] and I,[14] both advocated a very conservative approach to patient selection after long-term follow-up demonstrated that many patients (other than those with cancer pain) eventually had a return of their pain, a lesson that should not be lost on the reader.

The advent of imaging led to another improvement in percutaneous C2 cordotomy. Kanpolat[25] performs the procedure in the computed tomographic scanner, rather than using biplane x-ray, so the trajectory of the needle can be seen directly, and he reports considerable success (*Fig. 2.3*).[25] McGirt[33] described a similar procedure using the improved definition of magnetic resonance imaging.

Percutaneous cervical cordotomy inadvertently led to another procedure. Hitchcock[22] performed percutaneous cervical cordotomy at the cervicomedullary level with his stereotactic apparatus that allowed him to insert a suboccipital electrode from posteriorly until it lay in the anterolateral quadrant, which gave fine control over electrode placement. Even so, one patient experienced bilateral pain relief with widespread analgesia, and study of the intraoperative x-rays demonstrated that the electrode lay in the midline. This led Hitchcock,[23] and later Schvarcz,[46] to use such a midline placement of a lesion at high cervical levels as *extralemniscal myelotomy* for all types and locations of pain, with great success. However, as originally described, it could only be done with a stereotactic apparatus such as Hitchcock's[21] that allowed a suboccipital approach. Hitchcock[23] assumed that the target was a multisynaptic pathway ascending along the central grey, which would also explain the observations made earlier after myelotomy that pain relief extended far beyond the area of analgesia and included the entire area below the myelotomy, that pain relief could be obtained without sectioning the anterior commissure, and that myelotomy was particularly successful for visceral pain (*Fig. 2.4*).

After I had performed Hitchcock's procedure successfully with a C1 laminectomy, rather than stereotactically, it seemed to me to be excessive to make such a high lesion for a patient with pelvic or perineal pain. It was reasonable to think that pain relief of lower body or pelvic pain might be

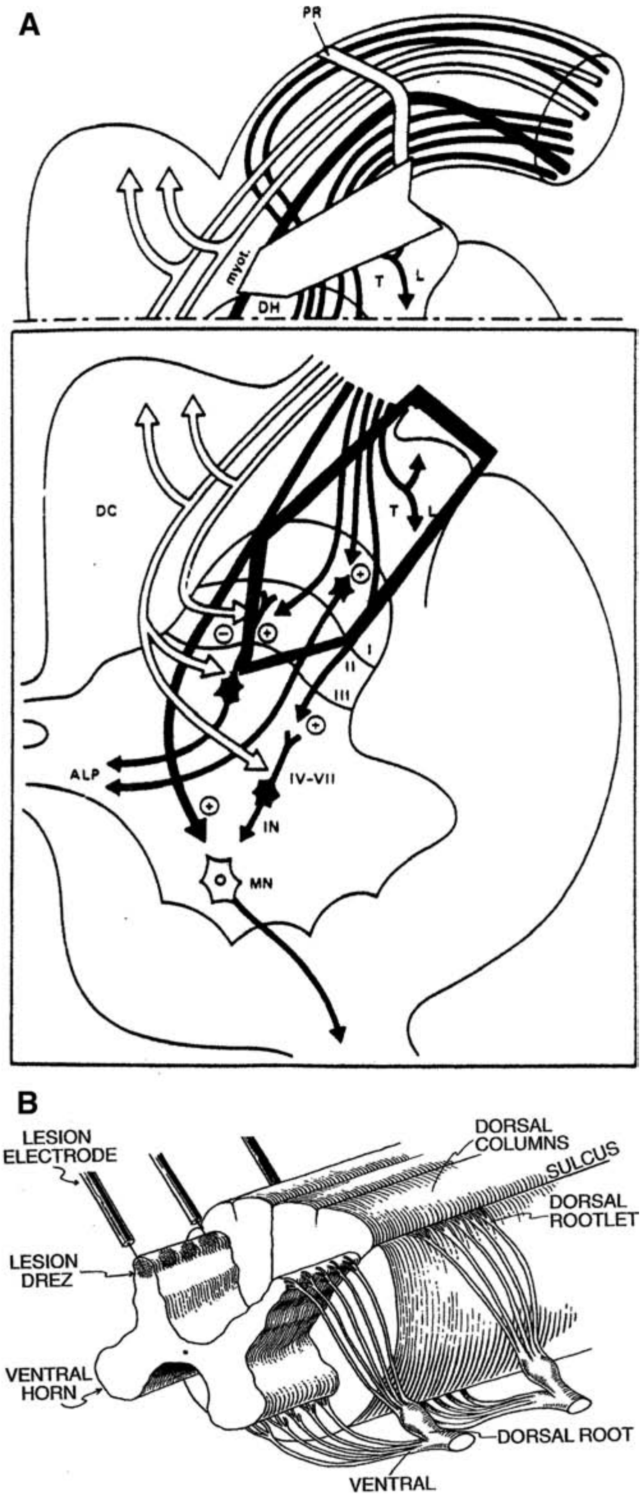

FIGURE 2.5. *A*, Sindou sectioned the small fibers as they entered the dorsal root entry zone. *B*, Nashold introduced an electrode into the DREZ to lesion the tip of the dorsal horn. (from, Nashold BSJ: Current status of the DREZ operation: 1984. **Neurosurgery** 15:942–944, 1984[38]).

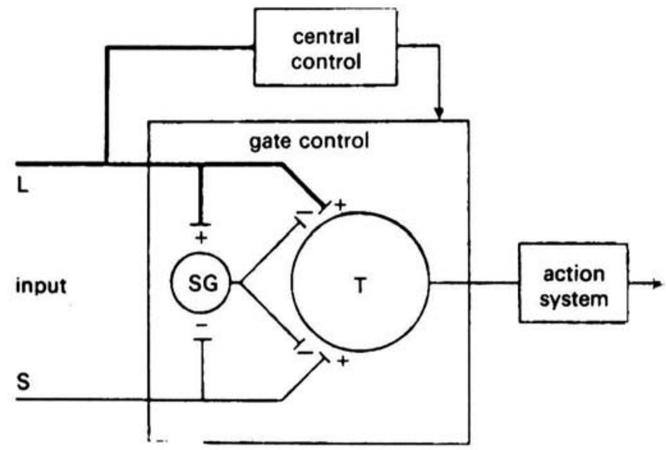

FIGURE 2.6. The Melzack-Wall gate theory opened the door to neuromodulation with chronic stimulation of the large fibers to close the gate to inhibit pain transmission at the spinal segmental levels in dorsal column stimulation. (from, Melzack R, Wall PD: Pain mechanisms: A new theory. **Science** 150:971–979, 1965[34]).

achieved with a similar midline lesion at the thoracolumbar spinal cord. After initial success in several patients, I recruited Richard Hirshberg, a neurosurgeon at a hospital with a large colon cancer service, to join in evaluating that procedure.[16] A T9 laminectomy exposed the T12–L1 level of the spinal cord, and a small ball-tipped dissector inserted into the midline made a sufficient lesion to provide consistent relief of bilateral and midline pelvic and perineal pain, particularly visceral pain. (Unfortunately, two major American neurosurgical publications rejected our report because "there is no such pathway," but the report appeared in a British journal.[17])

I speculated, as had Hitchcock[23] and Schvarcz,[45] that we were interrupting a previously unrecognized multisynaptic pain pathway at the medial edge of the dorsal columns. However, when Hirshberg provided Bill Willis[2] with a postmortem spinal cord specimen in 1996, interruption of a long tract was seen at that location, and subsequent animal studies documented that there was indeed a long pathway at the anteromedial dorsal columns involved with perception of pelvic visceral pain, which he has called the dorsal column visceral pain pathway. We named our procedure "*limited myelotomy*" to differentiate it from Hitchcock's cervicomedullary "*extralemniscal myelotomy*" and previously reported "*commissural myelotomy*," which was designed to interrupt decussating primary pain fibers over multiple segments. Kim[26] performed a similar procedure at high thoracic levels for chest, thoracic, and abdominal pain. When Nauta[40] later performed this same procedure by making multiple punctures of this pathway, he named it "*punctuate midline myelotomy*" (but erroneously reported that we and Hitchcock had performed commissural myelotomy).

Let us depart briefly from the chronology of spinal cord procedures for pain to discuss a final group of ablative procedures. As early as 1911, Cajal[7] noted that the large fibers entering the dorsal root gathered dorsally to become the dorsal columns, whereas the small nerve fibers gathered ventrally to enter the dorsal horn. When it was later appreciated that the small nerves subserve pain transmission, this separation of fibers at the dorsal root entry zone (DREZ) invited selective interruption of pain input into the spinal cord.[50]

This led Sindou[49] in 1974 to devise the surgical technique of *spinal entry zone interruption* to section the small pain fibers selectively as they enter the spinal cord more ventrally than the other dorsal root fibers. He made an incision into the spinal cord just ventral to the entering dorsal root over the involved segments, with good relief of pain (*Fig. 2.5A*). This further led Nashold,[39] in 1976, to develop a technique of introducing a radiofrequency needle-electrode into the dorsal root entry zone to interrupt the pain fibers just after they have entered the spinal cord, as well as the origin of the lateral spinothalamic tract, an operation he called the *DREZ procedure* (*Fig. 2.5B*). Both Sindou and Nashold found the procedure particularly good for denervation pain at the level of injury in paraplegic patients[39] and denervation pain from brachial plexus avulsion, as well as post-herpetic neuralgia[38]. Although these early DREZ area procedures spared Lissauer's tract, in 1999 Teixeira[56] modified the procedure by including that tract, harkening back to the old procedure combining cordotomy with Lissauer tractotomy. The advantages of these dorsal root entry zone procedures include their benefit for denervation or neurogenic pain, but disadvantages involve the need for multiple level spinal cord exposure and difficulty in predicting results.

To return to our chronology, the next advance to influence spinal cord surgery for pain was the presentation in 1965 of the Melzack-Wall gate theory[34] (*Fig. 2.6*). That theory proposed that stimulation of large non-pain sensory fibers would tend to close the gate and inhibit pain transmission, explaining the age-old observation that "when you rub it, it feels better." This suggested that electrical stimulation of the larger fibers might efficiently inhibit pain transmission. As the voltage is gradually increased, the first non-painful sensation indicates stimulation of the large nerves, whereas the first painful sensation indications that the small pain fibers are also being stimulated, which allows one to adjust the stimulation to involve just the large fibers and close the gate.

The first demonstration of electrostimulation producing analgesia was by Sweet and Wepsic[55] in 1967, when they stimulated their own infraorbital nerves. Because the large fibers turn dorsally on entering the spinal cord, the dorsal columns are almost a pure collection of such axons by anatomical coincidence,[34] and the dorsal surface of the spinal cord soon became the target of choice for chronic stimulation for pain management. *Dorsal column stimulation*, later called *spinal cord stimulation*, theoretically causes retrograde impulses to descend to lower spinal levels, at which they enter the dorsal root entry zone to "close the gate" and inhibit pain transmission (although later observations suggest a more complex mechanism). This concept led Shealy et al.,[47] in 1967, to develop an implantable stimulator to apply chronic stimulation to the dorsal spinal cord in a long-term nondestructive procedure to treat pain.[48] Their success led to the availability of implantable neurostimulators in 1968 for both spinal cord and brain stimulation.[13] Since that time, stimulators have become more efficient, have become fully implantable, have a longer-lasting power supply, are used with percutaneously inserted electrodes, and have been widely used throughout the world for spinal cord stimulation for treatment of persistent pain.

In 1983, spinal cord stimulation was advocated for pain of peripheral vascular ischemic disease.[10] It was soon found that blood flow was also improved by spinal cord stimulation, so a healing of ischemic tissue might occur if not too far advanced.[6] Soon after, spinal cord stimulation was also advocated for angina,[4] but with a concern that loss of the protective pain might lead to overexertion and myocardial infarction. However, it was demonstrated that coronary blood flow was also improved by spinal cord stimulation[31].

Despite the major advances in stimulator technology and surgery, the key to the successful use of spinal cord procedures for pain remains patient selection. As a general rule, destructive procedures should be reserved for cancer pain or pain of specific etiologies, such as root avulsion or postherpetic neuralgia. Stimulation procedures would be mostly used for persistent pain of benign origin, and then only with conscientious patient selection after noninvasive programs have proven inadequate.[14,15] Destructive procedures designed to interrupt pain pathways would best be reserved for patients with intractable cancer pain.

The evolution of spinal cord procedures for pain management is a classical example of how clinical opportunities emerge from basic knowledge and lead further to a better understanding of the function of the nervous system, the basis for applied neurophysiology.

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