Current Trends in Minimally Invasive Spinal Surgery

Erich O. Richter¹,², Marina V. Abramova¹, & Jason C. Mussell²

Abstract: The past 30 years has seen a dramatic expansion in the technologies available to practitioners of interventional pain management for the spine. This survey article spans the historical development from spinal decompression and fixation techniques to the most recent endoscopic and laser based therapies. This review is based on the six basic mechanisms for reducing pain of spinal origin: 1) anti-inflammatory/analgesic; 2) lysis of scar/de-tethering; 3) decompression; 4) arthrodesis/fixation; 5) neural ablation; and 6) neuromodulation. Multiple therapeutic modalities are summarized in each of these domains including; intradiscal electrothermy, epiduroscopy with laser ablation, percutaneous or endoscopic instrumentation and arthrodesis, vertebral augmentation, interspinous process decompression, percutaneous removal of the ligamentum flavum, intrathecal medication infusion, and spinal cord or peripheral nerve, neuromodulation. Intracranial pain techniques are beyond the scope of this article. Each technique is addressed from the standpoints of basic concepts and anatomy, as well as efficacy and complications.

Keywords: Epiduroscopy, minimally invasive, pain, laser, stimulation, fusion, neuromodulation

INTRODUCTION

Pain of spinal origin is an extremely common medical problem in the developed world, is a leading cause of disability, and has a markedly negative economic impact. Over the past 30 years, significant technological developments have advanced our ability to visualize and access spinal structures, including the epidural space. Additionally, understanding of the etiology and pathophysiology of spinal disease has advanced accordingly. The current era offers unprecedented technology for the diagnosis and treatment of pain of spinal origin. However, the proliferation has been so rapid that many practitioners are unsure of where these technologies sit in the overall clinical space. This overview attempts to provide a historical context for the development of each technology and provide a synopsis of each modality.

Each treatment modality will be addressed in the same fashion. First, a brief discussion of the distinguishing features of the therapy and the conceptual underpinnings of its development, along with any unique equipment involved, followed by an overview of indications, and finally a brief description of efficacy and complications. In this way, a snapshot of each therapy will help the reader form an understanding of how that treatment fits within the overall armamentarium of pain therapies.

In the end, there remain six basic mechanisms for procedural alleviation of pain (Table 1). Each therapy employs one or a combination of these basic mechanisms. Often, clinical advances are not in the actual therapeutic target or mechanism employed, but in minimizing the tissue disruption required to obtain that goal.

History

Several lines of development have occurred simultaneously in the development of spinal surgery for pain. In 1936, Stern described the spinascope for direct visualization of dorsal roots during rhizotomy in patients with intractable back pain, and lesioning of anterior roots in patients with spastic conditions [104]. During the same period, Pool performed the first myeloscopic procedure, with the aid of a modified otoscope with illumination, and later published his experience with 400 patients in whom he performed myeloscopic examination of dorsal nerve roots, hypertrophied ligamentum flavum, adhesive arachnoiditis, neoplasms, and metastatic carcinomas [77]. In 1955, Malis implemented the use of binocular microscopy and bipolar coagulation to facilitate his surgical approach [66]. In 1963, Smith studied the biochemical properties of the nucleus propulsus and performed chemical destruction using chymopapain [102]. After successful enzymatic dissolution of the nucleus propulsus by Smith, additional attempts were made using heat or laser technology to shrink the nucleus and alleviate clinical symptoms caused by nerve compression. During the 1970’s, with the introduction of intraoperative microscopy, Yasargil and Caspar introduced microdiscectomy for management of intravertebral disc disease [18, 112]. In 1984, Ascher and Heppner used a neodymium:

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yttrium-aluminum-garnet (Nd:YAG) laser to cauterize the nucleus pulposus for the direct relief of pain [8]. Since the 1990’s, minimally invasive surgery (MIS) based on tubular retractors has evolved rapidly and many automated techniques have been introduced for the removal of disk material. These techniques have since been refined with and without the use of the endoscope from a variety of approaches [71, 86, 103, 113].

Endoscopic approaches have been strongly tied to technological developments. Recently, [93-95] flexible epiduroscopy for decompression has allowed longitudinal anterior epidural access via a single caudal incision, filum terminale decompression and S4 laminotomy [54, 91]. The advent of the operating laser significantly advanced the power for intervention through such a small portal. The development of treatments for epidural fibrosis has had a similar progression from the early work of Racz [78, 79] with epidural infusions and the introduction of flexible, steerable catheters to the use of more elaborate steerable endoscopic units with laser and quantum molecular resonance fibers, and balloons for active neural scar decompression and tissue lysis [19, 80-83]. Arthrodesis, once accomplished exclusively through large incisions for instrumented posterolateral onlay fusions of iliac crest graft over the transverse processes [25], began to evolve with the use of segmental fixation [63]. This was followed by anterior interbody cage fusions [70], the use of biologics [114], synthetics [27], and machined allograft (Fig. 1) [49]. Percutaneous fixation, in the form of percutaneous pedicle screws [32], lead to the development of facet screws [32], percutaneous interbody solutions [115], percutaneous vertebral augmentation [10], percutaneous anterior fixation [7], and non-instrumented percutaneous facet arthrodesis [85]. For situations in which there is not a readily achievable structural cure, neuromodulation techniques have also advanced. Programmable intrathecal infusion pumps [73] are now widespread and spinal cord stimulation devices have seen a dramatic evolution in electrode configurations based on mathematical modeling of current flow. From the original quadripolar arrays [58], came eight contact systems [13]. Then paired eight contact arrays became available [2], followed by the transverse tripole configuration [45], and most recently the five column array [31]. Continuing along the minimally invasive trend, recently a percutaneous device for the insertion of paddle leads has been made available in some countries [101]. The availability of percutaneous systems that minimize trauma in the insertion of stimulators has caused a resurgence in the use of peripheral nerve stimulation due to its attractive risk-benefit ratio.

**Intradiscal electrothermy**

Intradiscal electrothermal therapy (IDET) was first introduced by Saal et al. in 1997 [97]. The rationale behind heating of the intervertebral disc was influenced by investigations into the ability of heat to stabilize joints by modifying collagen [29]. IDET uses laser radiofrequency heating devices to denature the collagen (Fig. 2). Type I collagen has a triple helical configuration that is responsible for the molecule’s ability to resist tensile forces. Heating breaks weak intramolecular bonds, damaging the

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<th>The Six Mechanisms of Pain Relief</th>
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<td>1. Anti-inflammatory/ Analgesic</td>
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<td>2. Lysis or removal of scar/ Untethering</td>
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<td>3. Decompression</td>
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<td>5. Neural Ablation</td>
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<td>6. Neuromodulation</td>
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Table 1. The six basic mechanisms for the procedural relief of pain of spinal origin.
Figure 3. Laser decompression of disc herniation. Direct visualization of the inflamed nerve root via a flexible epiduroscope allows access for a fiber optic fiber (seen in blue) and decompression of the nerve root. (Figure used with permission from Richter, 2011 [91]).

The use of lasers for treating discogenic pathology is becoming increasingly popular, and as Schenk pointed out, the potential medical and economic benefits appear to justify continued research and exploration [92, 93, 95, 98]. Choy introduced laser treatment for herniated nucleus propulsus in 1984 but only first reported his experiences with the ND:YAG laser in 1998 [21]. Hellinger et al. described the mechanism of action for laser treatments as threefold: 1) increased elastance, 2) decreased mass and bulk, and 3) collagen shrinkage [44]. Because the Holmium laser has superior tissue effects, when technological advances in the delivery systems made uses of the Holmium: YAG (Ho: YAG) feasible, it largely replaced the Nd: YAG lasers. The higher absorption rate of the Ho:YAG laser produces less charring and has a more shallow tissue penetration [108]. More recently, the Thulium:YAG (Tm:YAG) laser has been shown to have even more favorable tissue effects than the Ho:YAG Laser [62]. Two articles in this supplement report in more detail on these techniques. A detailed description of the technique is given in the article by Richter and Rothstein (Fig. 3) [91]. Kim at al report the evolution of their technique over a series of 109 patients, and contrast the results of their cases with mechanical treatment alone, those with laser assistance, and report that in their hands, the addition of the laser improved outcome compared to mechanical treatment alone [54]. Non-lumbar applications have also been recently described [5].

Percutaneous or Endoscopic Instrumentation and Arthrodesis

Percutaneous fixation of the lumbar spine was first described by Magerl using a temporary external fixator [64]. Mathews and Long then described a technique for percutaneous lumbar pedicle fixation with the aid of plates as longitudinal connectors [69]. Lowery and Kulkarni modified this technique using placement of rods, instead of plates [61]. Foley et al. performed pedicle screw internal fixation for lumbar fusion with good clinical results [33]. Kim et al. demonstrated that percutaneous pedicle screw placement caused less paraspinal muscle damage than open pedicle screw fixation [53] (Fig. 4). Ni et al. (2010) showed the efficacy of percutaneous pedicle screw fixation for thoracolumbar burst fractures [72].

Epiduroscopy

The use of lasers for treating discogenic pathology is becoming increasingly popular, and as Schenk pointed out, the potential medical and economic benefits appear to justify continued research and exploration [92, 93, 95, 98]. Choy introduced laser treatment for herniated nucleus propulsus in 1984 but only first reported his experiences with the ND:YAG laser in 1998 [21]. Hellinger et al. described the mechanism of action for laser treatments as threefold: 1) increased elastance, 2) decreased mass and bulk, and 3) collagen shrinkage [44]. Because the Holmium laser has superior tissue effects, when technological advances in the delivery systems made uses of the Holmium: YAG (Ho: YAG) feasible, it largely replaced the Nd: YAG lasers. The higher absorption rate of the Ho:YAG laser produces less charring and has a more shallow tissue penetration [108]. More recently, the
Percutaneous Facet Fusion

Goldthwaite pioneered the concept of the facet joint as a pain generator in patients with low back pain in 1911 [39]. Facet joint pain may be caused by a variety of pathologic processes including degenerative arthritis, systemic arthritis, villonodular sinovitis, synovial cyst, microfractures, joint subluxation, or synovial entrapment. When conservative management, median branch nerve blocks with local anesthetic and corticosteroids, and rhizotomy have failed, the patient may be offered lumbar fusion. Transfacet fixation was originally developed by King in 1948 [55]. Open facet fixation is established in many reports, but is rarely performed as a stand-alone procedure [30, 43, 55, 65, 67, 107]. Alternatively, a minimally invasive percutaneous facet fusion (Figs. 5, 6) can be used solely for treatment of facetogenic pain with minor instability (1-2 mm listhesis) or as an adjunct to an anterior interbody fusion. Percutaneous facet fusion disrupts the facet joints and provides stiff immobilization of the segment. There are two basic approaches to percutaneous facet fusion and fusion in widespread use at this time. One procedure (Fig. 5) consists of placing bone graft dowels under fluoroscopic guidance into the facet joint to limit movement and promote fusion. The dowels separate the joint surfaces so that the articular surfaces no longer bear load, provide bridging bone for fusion, and open the neural foramen. The stretch of the remaining joint capsule, particularly anteriorly, provides the resistance to opening the joint for a firm pressure fit, but there is generally no rigid instrumentation. There are no published reports to clarify the rate at which graft may “back out” over time. An alternative approach is to place percutaneous cannulated screw across the facet and into the pedicle of the inferior level (Fig. 6). In this technique the arthrodesis is simply from the drill crossing the articular surface of the facet, and additional graft material is usually minimal. Jang and Lee compared the efficacy of percutaneous facet screw fixation after anterior lumbar interbody fusion with post-ALIF pedicle screw fixation. After a minimum of 2 years...
follow-up, they found no statistically significant difference in terms of Oswestry Disability Index (ODI) and MacNab criteria [48].

**Axial Lumbar Interbody Fusion**

The Axial Lumbar Interbody Fusion (AxiaLIF) (TranS1®, Inc., Wilmington, NC) transsacral system was developed as an alternative method to transforaminal lumbar interbody fusion or posterior lumbar interbody fusion at the lumbosacral junction (Fig. 7). Cragg et al. initially introduced the technique in 2004 [24]. Indications for the procedure are the same as that of traditional anterior lumbar interbody fusion, transforaminal lumbar interbody fusion, or posterior lumbar interbody fusion. It is relatively contraindicated as a stand alone procedure in patients with neural compromise from compression, as it does not provide any direct decompression of the neural elements, and in patients with previous retroperitoneal surgery, as scarring may prevent free passage of the instrumentation. The transsacral approach accomplishes the goals of stabilization of the lumbosacral spine with a percutaneous, paracoccygeal, axial approach. It does not damage the annulus fibrosus and posterior longitudinal ligaments. Aryan et al. retrospectively reviewed the results of a multicenter study on the use of AxiaLIF in the treatment of L5-S1 degeneration [7]. Thirty five patients were included in analysis with average follow up of 17.5 months. Patients underwent AxiaLIF with pedicle screw fixation at L5/S1 (N = 21), stand-alone AxiaLIF at L5/S1 (N = 10), and/or AxiaLIF as part of a larger construct (N = 4). Overall fusion rate at one year follow-up was 91%. The mean visual analog scale for back pain (VAS) decreased by 44 (75→31) from the pre-op level and the ODI decreased by 20 (42→22) at one year follow up. The risk of infection related to paracoccygeal approach appears to be low because the procedure is short and performed percutaneously with minimal tissue devitalization and small anatomical dead space [68].

**Extreme Lateral Interbody Fusion**

This approach passes through the retroperitoneal fat and psoas muscle from a small lateral incision. The benefits of a minimally invasive lateral approach include: preservation of the anterior longitudinal ligament; avoiding opening the peritoneum; avoiding disruption of the great vessels and hypogastric nerve plexus. Injury to the hypogastric nerve plexus may lead to retrograde ejaculation. Tissue dissection is performed under direct visualization, which improves the learning curve (Fig. 8). Pimenta et al., who introduced this method in 2001, performed total disc replacement using Extreme Lateral Interbody Fusion (XLIF) in 36 patients with one or two-level lumbar degenerative disc disease [76]. Immediate postoperative complications were minor and included leg weakness and leg hypertrophy on the contralateral side which resolved within 2 years. In two patients (5.6%), revision of fusion was required. At the two year follow-up, the mean VAS score and ODI score improved 69.6% and 61.4%, respectively. Karikari et al. used a lateral approach for the management of thoracic and thoracolumbar spine disease [52]. Diagnoses were scoliosis, adjacent disc disease from previous surgery, thoracic disc herniations, discitis/osteomyelitis, and pathological fractures from tumor invasion. The series included thoracic XLIFs, from T6-7 to T11-12 and thoracolumbar approaches to T12-L1 and L1-2. All patients demonstrated radiographic fusion at 6 months follow-up. In patients with scoliosis, the mean preoperative and postoperative sagittal angles were 39 degrees and 44 degrees, respectively. The average improvement was 8 degrees in both coronal alignment and sagittal alignment. The mean VAS scores improved from 7.3 to 4.6 postoperatively, the ODI scores decreased from 42 to 34. Postoperative complications were minor: one subsidence of interbody graft into the
adjacent vertebral body, one adjacent level disease, and one wound infection.

The approach is anatomically most attractive in the upper lumbar spine. At more caudal levels, the bulk of the psoas muscle progressively increases, and care should be taken with neuromonitoring to avoid the nerve roots and lumbar plexus. The iliac crest prevents access to the L5/S1 space, and careful preoperative evaluation of the relationship of the iliac crest to the L4/5 level is needed in any given patient to determine if that level can be effectively reached.

**Vertebral Augmentation**

**Vertebroplasty**

Vertebroplasty, the injection of polymethylmethacrylate (PMMA) under pressure into the interstices of the trabecular bone of the vertebral body (Fig. 9), was first introduced as a treatment for vertebral angioma in 1984 [35, 36]. Later, indications for the procedure were extended to the treatment of painful compression fractures [11, 23]. Vertebroplasty is contraindicated in patients with hemorrhagic diathesis, infections, or lesions with epidural or foraminal extension associated with neurologic deficit, as extension into the epidual space may worsen the neurologic compromise. Good outcomes are reported in 78-96% of patients with osteoporosis; greater than 80% of patients with vertebral tumors; and greater than 70% of patients with hemangiomas [10, 28, 37, 116]. Reported immediate complications include: transitory worsening of pain (2.9%) [42]; transitory fever (5.9%) [42]; transitory nerve root pain (5.9%) [42]; cement pulmonary embolism (2.9-4.3%) [42, 50]; and rib fracture (4.3%) [50]. Cement leaks are common, but often unreported, as the clinical significance is unclear. Reported rates of asymptomatic leakage range between 11 and 73% [38, 99, 106, 110].

Although a large body of retrospective studies showing the efficacy of percutaneous vertebroplasty exists, controversy arose when two randomized clinical studies showed no difference between conservative treatment, sham therapy, and percutaneous vertebroplasty [51, 96].

Kyphoplasty was introduced in 1998 (Fig. 10) [12]. The distinguishing difference between kyphoplasty and vertebroplasty is the creation of a cavity in the vertebral body by inflating a “balloon tamp”, followed by a low pressure injection of PMMA. Accordingly, cement leakage after kyphoplasty is lower (9% vs. 41%) [46]. The relative importance of cavity creation compared to cement viscosity and injection volume in preventing cement leakage and other complications remains unclear [17]. In a recent randomized trial, Boonen et al. [15] reported that kyphoplasty lead to greater improvement in SF-36 score compared to non-surgical treatment when averaged across the 2 year follow-up period, but this difference did not persist in significance at the 2 year mark. Liu et al. showed no difference with kyphoplasty in patients with osteoporotic vertebral compression fractures at 6 months follow-up [55], however, Kumar et al. did find a more favorable outcome measured over long-term follow-up [59]. A recent meta-analysis associated kyphoplasty with favorable outcomes in patients with malignant vertebral fractures at two years follow-up [16]. Although controversial, most literature suggests kyphoplasty is superior to non-surgical treatment [109].

Driven by recognition that the procedural terminology (CPT) coding language for kyphoplasty was essentially brand specific, recent changes have allowed new devices to be marketed that meet the criteria for “cavity creation” and employ a variety of techniques to prevent extravasation of cement and allow a low pressure injection. One such example is the Osseeoflex® steerable needle (DePuy Spine, Inc., Raynham, MA) (Fig. 11) which features a large, steerable trocar that articulates across the vertebral body and fracture line, from a single pedicle. A particularly viscous cement formulation is used to prevent extravasation, and multiple passes of the large trocar create the cavity for the low pressure injec-
The single portal of entry has obvious advantages for both the surgeon and the patient. Other methods of cavity creation include radiofrequency devices for oncologic applications [47, 84], and some are discussed elsewhere in this supplement [84].

INTERSPINOUS PROCESSES DECOMPRESSION

The XStop® interspinous spacer (X-Stop®, St. Francis Medical Technologies, Inc, Alameda, CA) (Fig. 12) received FDA approval for the treatment of neurogenic claudication secondary to lumbar spinal stenosis in 2005. Since then, a number of related interspinous devices have been released under the 510(k) regulation mechanism, some of which are intended as fixation devices to supplement fusion. Patients with lumbar spinal stenosis (LSS), whose symptoms are completely alleviated with flexion and exacerbated with extension of the lumbar spine, can be considered for ISPD. Many surgeons also consider ISPD for facet pain. Studies of varying evidence levels, including level 1, are available for safety and efficacy, particularly for the X-Stop® device. Kuchta et al. reported 2 year follow-up results of the X-Stop® interspinous spacer in 125 patients with neurogenic claudication secondary to lumbar stenosis, excluding patients with previous fusion, laminectomy, or spondylolisthesis greater than grade 1 [57]. At two years of follow-up, the mean VAS score decreased from 61.2% preoperatively to 39%, and the ODI decreased from 32.6% to 20.3%. Eight patients (4.6%) required removal due to unsatisfactory effect. Contraindications include neural deficit, infection, coagulopathy, or markedly abnormal local anatomy precluding the ability of the device to produce a focal kyphosis. In a multicenter, prospective, randomized trial, Zucherman et al. evaluated the efficacy of the X-Stop® interspinous spacer over conservative therapy [117]. At 2 years follow-up, symptom severity scores improved by 45.4% from baseline in the X-Stop® group versus 7.4% improvement in the conservative management group. Additionally, the mean physical function scores improved by 44.3% in the X-Stop® group while the control group worsened by -0.4%. Device related complications were minor and included malposition in 1 patient (1%), implant migration in one patient (1%), one case of spinal process fracture (1%), and increased pain at the implant level in one patient (1%). Even with favorable level 1 evidence, the long-term clinical benefit of the X-Stop® interspinous spacer remains controversial. Despite statistically significant improvement of X-Stop® patients compared to controls, analysis of the Zurich Claudication Questionnaire showed that only 48% of the patients treated with X-Stop® satisfied all three Zurich Claudication Questionnaire criteria [14]. In addition, the concern remains as to whether the device truly is associated with a minimal complication rate. The reader is directed to Benzel’s recent editorial [14] for a full discussion of this controversy.

MINIMALLY INVASIVE LUMBAR DECOMPRESSION

Minimally invasive lumbar decompression (MILD) (Fig. 13) is a percutaneous technique for the decompression of lumbar stenosis due to hypertrophy of the ligamentum flavum. Essentially, it is a fluoroscopically placed, percutaneous ronguer with a modified tip to prevent dural injury. This technique is reviewed extensively by Deer...
et al. in this issue [26], including patient selection and potential complications. Chopko and Caraway reported preliminary results of a prospective multicenter study on the efficacy of the MILD procedure in patients with symptomatic central canal spinal stenosis showing significant improvement in VAS, ODI, Zurich Claudication Questionnaire, and SF-12 quality of life physical and mental component scores at 6 weeks follow-up with no major complications [20].

**INTRATHecal MEDICATION INFUSION**

Several classes of drugs can be administered intrathecally (IT) for spasticity and pain management, including: opioids; local anesthetics; nonopioids acting on the spinal adrenergic, or GABA, receptors; and baclofen. The relatively low doses required with IT administration of most medications for adequate clinical effect has proven beneficial for patients that experience severe side effects from oral/parenteral administration (Fig. 14) [22]. IT administration of morphine has excellent anesthetic properties, and selectively blocks the nociceptive opioid receptors at the posterior horn of the spinal cord. Most reports suggest that a three to five fold dose increase over the 30 weeks is typical [73]. Onofrio and Yaksh assessed long-term pain relief after intrathecal administration of morphine in patients suffering from terminal metastatic disease. They demonstrated the efficacy of intrathecal morphine in patients with cancer pain to be 65% after more than 16 weeks of drug infusion [73].

**SPINAL CORD AND PERIPHERAL NERVE STIMULATION**

The technical understanding of spinal cord stimulation (SCS) has advanced dramatically over the last 5 decades. Initially, SCS implants progressed from single column quadripolar systems to multipolar paddle leads with single column and dual column designs (Fig. 15). Despite these technical developments, the treatment of lower back pain remained a challenge. Although SCS implants often provided good paresthesia coverage initially, patients would often return with loss of paresthesia coverage and pain relief in the low back. The work of Struijk and Holsheimer showed that the transverse tripolar configuration allowed precise targeting of the more medially located dorsal column fibers, and therefore might be more effective in capturing low back pain and controlling undesired paresthesia patterns in the dorsal roots [105]. Transverse tripolar stimulation provides an optimal electrical field for stimulation of the fibers of the low back while avoiding stimulation of the dorsal root [60]. To date, several transverse tripolar stimulation systems are available based upon the pain pattern that needs addressed. Shorter transverse tripolar leads are used for the treatment of back pain alone, and longer electrodes are usually used for treatment of both leg and back pain [60]. Despite these technological advances, complex multifocal pain remained extremely difficult to manage. This lead to the introduction of a five-column lead (Penata®, St. Jude Medical, Inc, Plano, TX) in 2009 [31]. The main advantage of this new multicolumn lead is the ability to finely direct the current in medial-to-lateral pattern rather than rostrocaudally [1]. Preliminary results demonstrate the utility of this lead and favorable outcomes in the treatment of complex pain syndromes [4, 31, 87-90].
Peripheral nerve stimulation

Since its inception in the 1970’s, peripheral nerve stimulation (PNS) has become increasingly popular in the treatment of chronic neuropathic disorders. The introduction of percutaneous cylindrical SCS type electrodes [111] increased the spectrum of PNS applications, including cranial, occipital, lumbar, sacral, genitofemoral, ilioinguinal, axial, segmental and ilio-hypogastric nerves [3]. To be effective, percutaneous PNS electrodes need to be placed in the vicinity of the painful peripheral nerves—close enough to elicit appropriate sensory paresthesia in the painful area [6]. For example, occipital nerve stimulation (ONS) leads are placed in a manner that provides stimulation of subcutaneous tissues innervated by the distal C1, C2, C3 posterior primary rami. As an adjunct to ONS, ultrasound can be used to allow real-time localization of both nervous and vascular structures. Skaribas and Aló showed that electrodes placed within 7 mm of the nerve under ultrasound provided consistent paresthesia into the back of the head [100]. Most implants are bilateral lead placements at or near the level of C1 [3]. Subcutaneous peripheral nerve field (PNFS) stimulation is a stimulation of the small endings of the distribution of the nerve within the subcutaneous tissue, directly underneath the dermis. The areas where PNFS is particularly effective include the lumbar area (Fig. 16), the posterior thoracic area, the scapular area, the inguinal area, and various regions of the head and face. PNS can also be used in the treatment of disorders associated with the brachial plexus [41], the lumbar plexus [75], single peripheral nerves [40], the paravertebral space [9], and the sympathetic chain [56].

Figure 15. A selection of currently available spinal cord stimulation electrodes. A. percutaneous and paddle leads from Medtronic Neurologic (Medtronic, Inc, Minneapolis, MN, used with permission). The second paddle has 8 contacts and is hinged in the middle to allow it to assume a curved lie against the dura. B. An assortment of tripolar paddle leads from St. Jude Medical (St. Jude Medical, Inc., Plano, TX, used with permission). C. A five column paddle lead (Penta™ electrode, St. Jude Medical, Inc, Plano, TX, used with permission). D. Percutaneous and paddle leads by Boston Scientific (Precision Plus™ SCS leads, Boston Scientific, Inc, Natick, MA, used with permission).
CONCLUSION

Technological advances have led to a wide variety of treatment options for patients with pain of spinal origin. Many of these are minimally invasive technologies that decrease the trauma associated with surgery. We have reviewed many of these technologies in this brief survey, and attempted direct the reader to sources of more detailed information on procedures in which they may have particular interest. We hope this review of the basic mechanisms of pain control, and how these procedures attempt to accomplish them has been useful. IDET is primarily a form of neural ablation, with some effect of indirect decompression from tissue shrinkage. Epiduroscopic approaches allow for multilevel decompression and lysis of adhesions over multiple levels from a single small incision. Specially designed instruments can decompress posteriorly based on epidurography alone. Multiple techniques have developed to allow for minimal access fixation and arthrodesis, including the fixation of vertebral augmentation. Interspinous decompression is a form of indirect foraminal decompression, and with some devices a form of fixation. Intrathecal pumps change the pharmacology of the local environment, and stimulator devices have neuromodulatory effects. When these techniques are mastered collectively, they can provide a powerful armamentarium for the treatment of spinal pain with all six of the possible mechanisms.

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