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Percutaneous Spinal Interventions

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Interventional neuroradiology (INR) procedures of the spine are being performed with increasing frequency. These therapies complement and, in some cases, replace more conventional operations of the vertebral column and its contents. This article surveys the background, present application, and future horizons of several minimally invasive spinal interventions, including vertebroplasty and kyphoplasty, microcatheterization of the cervical epidural space via lumbar puncture for drug delivery, percutaneous intraspinal navigation, and percutaneous spinal fixation.

Percutaneous spinal osteoplasty

Percutaneous transpedicular polymethylmethacrylate (PMMA) vertebroplasty consists of the injection of acrylic cement into a partially collapsed vertebral body in an effort to relieve pain and augment mechanical stability in the management of vertebral compression fractures (VCFs) secondary to osteoporosis, aggressive hemangioma, myeloma, and osteolytic metastasis [1].

The mechanism underlying the palliative effects of vertebroplasty is not well elucidated. Injection of cement fortifies weakened segments of the vertebral column and may reduce pain by halting further compression, deformity, or micromotion. Alternatively, it has been proposed that the heat generated by the exothermic polymerization of PMMA damages pain-sensitive nerve endings within the vertebra and surrounding tissues. Others believe that analgesia results from leaching of the PMMA monomer, which may be toxic to nervous tissue. Thermal necrosis and toxic effects of the monomer may account for the antitumoral effects noted after vertebroplasty performed for spinal metastases [1].

A more recent variant, kyphoplasty, attempts to restore lost vertebral body height and reduce the kyphotic deformity associated with VCFs. In this method, an inflatable bone tamp (Kyphon, Santa Clara, California) is introduced percutaneously into the collapsed vertebral body. As the tamp is expanded, cancellous bone is compressed and the end plates are lifted, creating an *en masse* reduction. After tamp removal, the subsequent void can be filled with PMMA under lower pressure than that needed for conventional vertebroplasty, thus potentially reducing the risk of cement leakage [1].

The indications, technique, and outcomes of vertebroplasty and kyphoplasty have been widely published [1,2], but it is imperative to realize that neither procedure has ever been subjected to prospective randomized trials contrasting it to the natural history of VCFs. Furthermore, kyphoplasty and vertebroplasty have never been directly compared in any study. Thus, the purported benefits of one procedure over the other remain speculative.

Although percutaneous vertebroplasty under radiographic guidance was first performed in 1984, its use has grown exponentially in the past several years. The potential reasons for this phenomenon include the following:

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1. Aggressive marketing campaigns
2. Recent technical innovations and instrumentation enhancements (eg, kyphoplasty)
3. The enfranchisement of neurosurgeons, orthopedic surgeons, and other nonradiologist practitioners
4. The growing number of neurosurgeons with hybrid training in INR techniques
5. An ever-aging population with commensurate increases in the incidence of osteoporotic spinal compression fractures
6. The pervasive trend toward therapeutic minimalism

Patient selection

Osteoporotic compression fractures of the spine occur in 700,000 patients annually in the United States and are twice as frequent as fractures of the hip. Because of evolving demographic changes, the incidence of osteoporotic fractures is expected to increase fourfold during the next 50 years.

Eligible patients for vertebroplasty and kyphoplasty are those who suffer from disabling back pain or impaired mobility secondary to VCFs with varying pathologic findings. These procedures have been applied to all segments of the spine, including the sacrum [3].

Most patients have failed trials of conservative therapy, consisting of analgesics, bed rest, or external bracing. All patients should undergo various combinations of plain films, CT, radionuclide bone scans, or MRI to delineate the fracture pattern and to exclude other treatable causes of pain, such as a herniated intervertebral disk. Patients with severe spinal stenosis or intracanalicular fragments are excluded, although some centers in Europe have reported good results treating burst fractures of the thoracic and lumbar spine.

Because osteoporosis is a diffuse condition, patients may have multiple VCFs of uncertain age, because up to two thirds of osteoporotic compression fractures never come to clinical attention. In such instances, nuclear medicine imaging is useful to help differentiate the symptomatic level from incidentally discovered fractures. Increased activity revealed on bone scans is highly predictive of a positive clinical response to percutaneous spinal osteoplasty. In other patients, increased edema within the marrow space of the vertebral body on MRI, best visualized on sagittal T1-weighted spin echo sequences, is indicative of a healing (acute or subacute) fracture amenable to these procedures. Up to three to four levels may be treated simultaneously at any one session [1].

History and physical examination also guide patient selection. Patients should be excluded if their pain fails to localize to the vicinity of the fracture, if the affected level is completely free of pain on palpation, or if there is an overwhelming radicular component to the pain, because the response to percutaneous spinal osteoplasty in such cases is unsatisfactory.

Surgical technique

The surgical technique of percutaneous spinal osteoplasty has been reviewed elsewhere [1,4]. Vertebroplasty is generally performed under local anesthesia along with intravenous neuroleptic anesthesia, using small doses of a narcotic for analgesia and a benzodiazepine for sedation and amnesia. Kyphoplasty, which is more painful because of the larger caliber of the instruments and the requirement for bone tamp inflation, is typically performed under general anesthesia.

Regardless of whether the procedure is conducted in the operating room or the INR suite, strict sterile protocol must be applied. After positioning the patient prone, the fractured level is visualized fluoroscopically and the needle entry sites overlying its pedicles are localized. For many cases of vertebroplasty, a unilateral approach is sufficient, but kyphoplasty requires placement of needles through both pedicles.

The skin and periosteum are locally anesthetized. A cannulated bone needle is inserted percutaneously and seated against the periosteum. Under fluoroscopic guidance, the needle is advanced through the middle portion of the pedicle into the anterior third of the collapsed vertebral body (Fig. 1). Recently, the adjunctive use of isocentric three-dimensional fluoroscopy-based navigation to guide placement of the cannula through the pedicle has been reported [5]. With image guidance, total duration and intraoperative fluoroscopy time were shorter than for procedures using biplanar fluoroscopy alone. Some groups advocate the use of CT during needle placement instead of fluoroscopic guidance.

Alternative techniques exist for gaining percutaneous access to the vertebral body, including the paraspinal route, which approaches the vertebral body from its posterolateral aspect. This trajectory is similar to that used for discography and arthroscopic disk excision. Proponents argue that

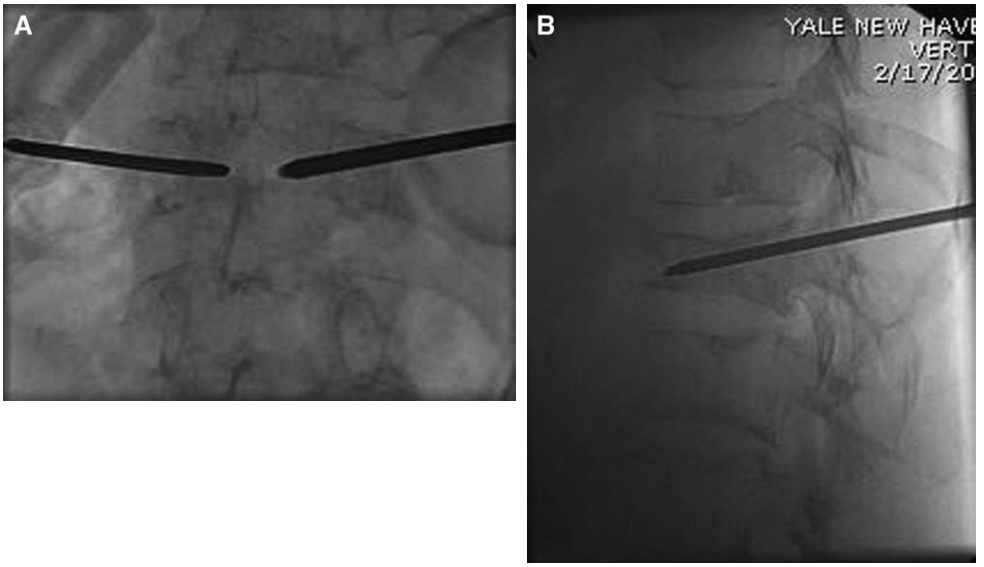

Fig. 1. Frontal (*A*) and lateral (*B*) radiographs demonstrate placement of cannulas through pedicles into the anterior third of the vertebral body.

the transpedicular approach places the nerve root and spinal cord at greater risk of injury, especially in the thoracic spine, where tolerances and pedicle sizes are smaller than in the lumbar region. Conversely, the paraspinal technique places several visceral structures at risk, including the lungs, kidneys, great vessels, segmental spinal arteries, and colon. Furthermore, with this approach, there may be a greater likelihood of cement leakage from the vertebral body once the cannula is removed [1].

Before cement delivery, some practitioners perform transosseous venography by injecting nonionic contrast material through the cannula. Rapid and brisk filling of the perimedullary veins or the inferior vena cava may indicate an increased risk of pulmonary embolism or epidural compression when cement is subsequently injected into the vertebral body. Venography may also help to evaluate the filling pattern and identify potential sites of PMMA leakage outside the vertebral body.

A variety of PMMA bone cements are commercially available, although many are not approved by the US Food and Drug Administration for spinal osteoplasty. The PMMA is mixed with an opacifying agent and, depending on operator preference, antibiotic powder. Under continuous fluoroscopic monitoring, cement is injected into the interstices of the vertebral body. Several delivery systems are available, although we prefer a volumetrically controlled screw-system syringe for injection of the high-viscosity cement. Compared with conventional syringes, the threaded plunger affords greater control of the injection pressure and quantity of cement delivered.

During kyphoplasty, cement delivery is customarily achieved using a series of ''bone filler device'' (BFD) tubes. Each BFD must be manually loaded with cement, which is then injected into the kyphoplasty cavity by manually depressing an inner stylet. The high profile of the BFD cannulas and their stylets requires frequent repositioning of the image intensifier tube and table. Because each accommodates only a small volume, the BFDs must be exchanged frequently. This delivery method also places the operator's hands directly in the field of radiation. Because of these limitations, we substitute the screw-system syringe injector used to deliver cement during conventional vertebroplasty for the BFDs. This amalgam has several merits over the customary means of cement delivery during kyphoplasty [6].

Care must be taken to avoid extrusion of cement beyond the confines of the vertebral body and inadvertent filling of the spinal canal, neural foramina, intervertebral disk spaces, or vertebral venous plexus. Cement is introduced until at least 70% of the vertebral body is filled. Ideally, the cement permeates the anterior three

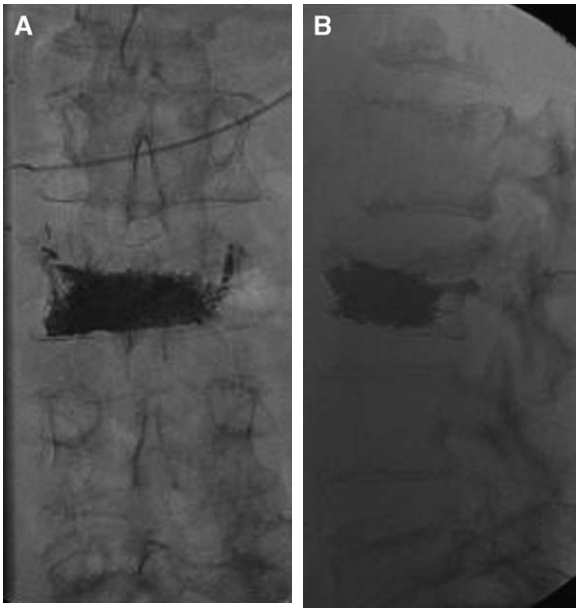

Fig. 2. Frontal (*A*) and lateral (*B*) radiographs after injection of polymethylmethacrylate cement mixed with barium. Ideally, the cement permeates the anterior three quarters of the vertebral body and at least two thirds of its transverse dimension.

quarters of the vertebral body and at least two thirds of its transverse dimension (Fig. 2). At the conclusion of the procedure, the needle is withdrawn. Antibiotic ointment and a sterile dressing are placed over the skin puncture site. The patient is placed on bed rest for 2 hours while the cement cures into a hardened state and is then discharged to home the same day unless general anesthesia is used.

Results

The response to vertebroplasty and kyphoplasty is generally favorable, with most series demonstrating a 75% to 90% likelihood of significant pain relief in properly selected patients [1,2]. Narcotic and analgesic requirements typically decrease. Sleep, ambulation, and other activities of daily living are improved. In many cases, pain relief occurs immediately. Results are durable, although recurrence of pain may occur from the development of a new VCF at an additional level.

When kyphoplasty was introduced, one of the earliest claims advanced by its proponents was the potential to restore lost vertebral body height and reduce the associated kyphosis. Some studies lend credence to this contention. Quantitative morphometric analysis before and after kyphoplasty demonstrates a significant reduction in vertebral body deformity as result of treatment [7]. In contrast, other studies have failed to demonstrate any restoration of vertebral body height [8]. Nevertheless, patients in the latter studies experienced profound clinical improvement. Thus, the impact of kyphoplasty on spinal alignment and the relation of this effect to pain relief remain unresolved controversies.

Complications of vertebroplasty and kyphoplasty include pulmonary embolism of cement, which can be fatal. Extrusion of PMMA cement beyond the confines of the vertebral body is observed commonly (up to 73% in some series). Although most cases are asymptomatic, several instances of spinal cord compression and myelopathy have been reported, with only modest recovery in neurologic function after emergency laminectomy. Nerve root compression with radicular pain or weakness may result from cement extrusion into the neural foramen. Other potential risks include cerebrospinal fluid (CSF) leak and infection, which may require corpectomy. Because most patients undergoing these procedures are elderly, pneumonia, myocardial infarction, and other medical complications may also occur [1].

Future directions

PMMA cement has a number of undesirable attributes, including the potential for thermal necrosis and its inability to integrate with the skeleton. In addition to acrylic polymers, such as PMMA, the transpedicular vertebroplasty technique permits the percutaneous delivery of several biocompatible materials into the vertebral body. Future treatment of compression fractures is likely to consist of injecting materials like hydroxyapatite, hormones, osteogenic growth factors, allograft or autograft, and other agents that induce bone regeneration. Biodegradable bone mineral substitutes that resorb as the bone remodels are currently being evaluated, as are osteoconductive materials, such as coral exoskeleton [1]. Newer systems for vertebral augmentation are likely to combine minimally invasive surgical access with bioactive injectable material to restore vertebral body height and sagittal alignment, provide structural stability by sustaining physiologic loads, and allow for the incorporation of graft material into native vertebral bone [1,9].

Cervical epidural microcatheterization

Deposition of anti-inflammatory or analgesic medication into the epidural space is a useful adjunct in the management of several spinal disorders, including pain of discogenic and spondylitic origin [10]. In addition to providing temporary relief of pain, the response to epidural drug therapy may help to predict surgical outcomes, thus maximizing the likelihood of a successful operation. Because these degenerative changes can affect every vertebral level, epidural analgesia and steroid infusion over long segments are potentially beneficial. The effect of this therapy is restricted to the spinal levels adjacent to the site of delivery, however, because of limited diffusion of medication within the epidural space. In practice, epidural injections are most commonly performed in the lumbar region, because anatomic factors make thoracic and cervical epidural access more hazardous. Risks of direct puncture of the latter areas include spinal cord injury and myelopathy, infection, bleeding, and pain.

Contemporary microcatheter technology has allowed remote access of confined anatomic spaces within the vascular system. The flexibility and low profile of these new devices minimize trauma and distortion of nearby structures. Application of endovascular technology and techniques allow placement of a microcatheter into the cervical epidural space via lumbar puncture for the purpose of drug delivery.

Surgical technique

The patient is brought to the INR suite and positioned prone. The midline of the lower back is prepared and draped sterilely. Under fluoroscopy, one of the lumbar interspinous spaces is selected for access. Local anesthesia is injected into the subcutaneous tissue overlying this interspace. An 18-gauge Tuohy needle is then introduced between the spinous processes and directed under fluoroscopic guidance to the spinolaminar line. The stylet is withdrawn, and the needle is gradually advanced while attempting to inject small aliquots of air through a 10-mL syringe until the epidural space is encountered. Correct needle placement is confirmed by the injection of radiographic contrast [10].

Next, a 2.3-French angiography microcatheter with a coaxial 0.018-inch steerable guidewire is introduced through the lumen of the Tuohy needle. Under biplane fluoroscopic imaging, the guidewire is advanced cephalad through the epidural space, followed by the trailing microcatheter. Patients frequently report a pressure-like discomfort during transit through the thoracic region. Once the cervical epidural space is reached, the guidewire is removed and a small amount of additional contrast is injected to confirm the absence of intravascular or intrathecal filling. Steroid medication can then be delivered through the microcatheter. Narcotics are avoided at this region because of the risk of respiratory depression. As with other epidural or nerve root blocks, reproduction of the patient's symptoms during the injection often signifies the appropriate anatomic level. In patients with concurrent spondylitic and discogenic changes of the thoracic spine, the catheter can be withdrawn to the symptomatic site, where additional steroid and narcotics are administered for regional analgesia.

Results

More than 40 cervical epidural microcatheterization procedures have been performed. Eligible patients suffered from spondylitic or discogenic disease of the cervical spine and presented with arm, neck, shoulder, or interscapular pain. In addition, several had radicular or local pain referable to degenerative changes in the thoracic spine.

In follow-up averaging 12 weeks (range: 4–12 weeks), all patients reported relief of varying extent and duration [10]. The results of cervical epidural steroid administration via this technique were similar to those with lumbar epidural steroid treatment and are generally consistent with the variable efficacy of epidural corticosteroids reported in the literature.

No procedures were aborted because of anatomic constraints or technical limitations, even among patients with severe spinal stenosis. There has been no clinically apparent infection, epidural hematoma, arachnoiditis, spinal cord injury, nerve root damage, CSF leak, or other complication.

Percutaneous intraspinal navigation

Recent advances in catheter technology and imaging allow potential new applications outside the vascular system. A percutaneous approach to cerebral access using the spinal subarachnoid space has been devised and tested in cadavers [11]. In this method, needle puncture allows for placement of an arterial introduction sheath within the lumbar cistern. Guidewires and catheters can then be introduced through this sheath and traverse the subarachnoid space until the intracranial contents are encountered. Intraspinal navigation and monitoring of guidewire and/or catheter position may be conducted with standard fluoroscopy. Alternatively, steady-state free precession MRI guidance may be used to track device position [12]. This imaging modality provides adequate contrast and temporal resolution to facilitate real-time MRI-guided intracranial and intraspinal navigation.

The subarachnoid space ventral and dorsal to the spinal cord has been traversed with relative ease. In limited analysis of cadaveric specimens, neither the guidewire nor the catheter has caused spinal cord violation or laceration [11]. No significant disruption of the epidural vasculature was identified.

In theory, percutaneous intraspinal navigation may serve many potential functions. Intracranial applications could possibly include ventricular catheterization, brain biopsy, depth electrode implantation, electrophysiologic recording, delivery of interstitial brachytherapy, and thermal ablation [11]. Endospinal MRI of the thoracic and cervical cord may be performed by using an antenna and/or guidewire introduced into the subarachnoid space via percutaneous intraspinal navigation techniques. When compared with images obtained from a linear surface coil, images obtained with the endospinal coil showed significant signal-to-noise ratio (SNR) gains [13]. This advantage may allow superior imaging in spinal cord injury and other disease states. The high SNR of the endospinal coil might also be exploited for magnetic resonance spectroscopy and diffusion-weighed imaging of the spinal cord, which have not been optimized using current surface coil technology [13].

Although percutaneous intraspinal navigation has only been studied in cadaver and canine experiments to date, continued evolution of catheter and imaging technology may allow its clinical application in the future.

Percutaneous spinal fixation

Back and neck pain affects up to 80% of Americans at some time in their lives. Greater than 150,000 lumbar and nearly 200,000 cervical spinal fusions are performed each year to treat common spinal disorders, such as degenerative disk disease, spondylolisthesis, and vertebral column trauma.

Posterior instrumentation is frequently used to augment anterior and posterior lumbar interbody fusions as well as cervical and thoracic fixation. Pedicle screws and rods are commonly used for this purpose. Traditional open surgical methods for the insertion of posterior instrumentation have several disadvantages, including the risk of significant blood loss, the potential for serious infections, and the need for extensive paraspinous muscular dissection to expose the anatomic landmarks for screw insertion, achieve proper screw trajectory, and develop a suitable fusion bed [14]. The tissue injury resulting from this dissection may lead to muscular denervation and necrosis, resulting in prolonged postoperative pain and disability.

Because of these limitations, tissue-sparing techniques to achieve spinal fixation have been sought. Minimally invasive approaches have been applied to a wide range of procedures, including anterior, posterior, and transforaminal lumbar interbody fusions; posterolateral onlay fusion; and pedicle screw and rod placement [14].

Early in the evolution of minimally invasive spinal fixation, endoscopes were used to minimize the size of the incision required to develop the

surgical corridor. In contrast, the Sextant system (Medronic, Minneapolis, Minnesota) enables the minimally invasive placement of percutaneous pedicle screws and rods in a subfascial anatomic position similar to that of traditional open techniques using fluoroscopic guidance [14–16]. The Sextant system consists of specially designed, cannulated pedicle screws connected via a precontoured rod. A disadvantage of the precurved rod is difficulty in passing it between three adjacent pedicle screws or in the presence of bony impediments to rigid rod placement.

Recently, a new percutaneous minimally invasive spinal fixation system based on pedicle screws and inflatable rods was described [17]. The rods are inserted in a flexible state and harden after deployment, thus enabling them to be able to traverse and conform to complex pathways between multiple screws (Fig. 3). The rods are filled with a novel expandable composite of epoxy polymer and graphite fiber matrix, which exhibits strength comparable to that of metallic rods. All system components were found to be biocompatible and nonferromagnetic and to produce little magnetic resonance artifact. Compression and torque results for the construct were found to be comparable to those of standard metallic pedicle screw and rod fixation systems. The new system displayed a superior modulus of elasticity relative to standard surgical devices, however. The new system endured 5 million cycles of repetitive compressions without breakage or significant wear. The epoxy polymer used to inflate the flexible rods cured to approximately 53% of its final strength in 90 minutes, with a maximum external rod temperature of 40.5°C and no thermal damage to paraspinous musculature and other adjacent tissues in animal studies.

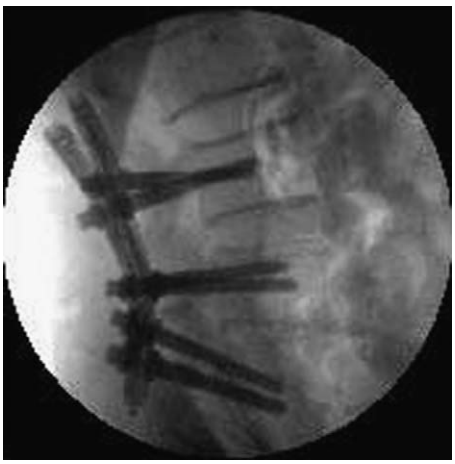

Fig. 3. Lateral radiograph demonstrating pedicle screw and inflatable rod spinal fixation system inserted percutaneously.

Because of its minimally invasive insertion, the new pedicle screw and rod fixation system may potentially reduce procedural morbidity, decrease paraspinous muscle denervation and necrosis, and speed postoperative recovery. Device characteristics eliminate the need for rod shaping and facilitate rod placement between more than two pedicle screws. These results support the concept that composite devices can be constructed in situ within the body using minimally invasive percutaneous INR techniques.

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