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Magnetic Resonance Imaging–Guided Spine Interventions

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DEFINITION OF PROBLEM AND CLINICAL PRESENTATION

The information available regarding procedural strategies for MR imaging–guided spine interventions is currently limited compared with that of more conventional radiation-based image-guidance techniques, such as fluoroscopy; however, interest and expertise are growing. With ongoing advancements in MR imaging techniques, new applications and opportunities are emerging, including those for treatment of low back disorders.

Low back disorders are widely prevalent. Low back pain is the leading cause of occupational disability worldwide, with lifetime adult prevalence varying from 50% to 80%.¹ Percutaneous image-guided spinal injections with corticosteroids and anesthetics are established therapeutic methods for low back pain. These procedures are traditionally performed with proved safety and accuracy under fluoroscopy or computed tomography (CT).^{2–4} Real-time CT guidance affords improved targeting because it allows cross-sectional visualization of critical anatomy, facilitates freehand real-time needle placement, and has the potential for more accurate placement into facet joints.^{4–6} However, there is an unavoidable risk of ionizing radiation associated with these techniques. This is a concern, particularly when these procedures are performed on young individuals of fertile age and serial therapeutic procedures are required.

MR imaging is an emerging modality in the guidance of various minimally invasive therapeutic interventions for low back pain because of the absence of ionizing radiation, the high soft tissue and fluid contrast, and multiplanar imaging options it provides. Newly developed MR imaging systems have been used in a variety of spine procedures for back pain including nerve root injection, facet joint injection, epidural injection, and facet joint neurotomy using cryotherapy. MR imaging–guided spine interventions are also available for the treatment and diagnosis of pathologic conditions, including biopsy and treatment of primary spinal tumors and metastatic disease.

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Because MR imaging is superior to other imaging techniques in depicting soft tissue and bone lesions in the spine, it is sometimes advantageous to use MR imaging when performing percutaneous biopsies. It allows for the accurate targeting of the lesion to be biopsied and clearly depicts critical structures that need to be carefully navigated to reach the target. In addition, MR imaging often provides superior depiction of the internal composition of lesions, allowing for targeted site-specific biopsies of heterogeneous lesions.⁷ Therefore, MR imaging can be used full circle with the detection of the initial lesion, planning and guidance for the biopsy of the lesion, and monitoring of treatment response following biopsy. MR imaging-guided biopsy does, however, require specialized biopsy equipment that is compatible with the MR imaging environment and that has limited susceptibility artifact.⁸

New applications of MR imaging-guided spine interventions are emerging, especially in the treatment of patients that are considered poor surgical candidates. Approximately one-half of the patients with metastatic disease have poorly controlled pain.^{9,10} Frequently, these patients have exhausted conventional therapies; therefore, percutaneous treatments have emerged to reduce pain, allow for local tumor control, and improve quality of life. MR imaging-guided interventions reduce morbidity compared with that of surgery and other conventional techniques, such as radiation therapy, by using a percutaneous approach with only one to a few tiny skin punctures needed to insert the biopsy needles or treatment probes.

One emerging treatment option is MR imaging-guided cryotherapy for the treatment of bone and soft tissue metastases and some primary tumors. Because the MR imaging signal is temperature sensitive, MR imaging can be used to monitor thermal ablation that during cryotherapy is visualized as an area of decreased signal intensity surrounded by a rim of hyperintensity on T2-weighted images, often referred to as an “iceball.”¹¹ The shape and size of the cryotherapy iceball is easily monitored and can be tailored in real time using multiple planes on MR imaging. MR imaging, well known as far superior to other imaging techniques for the depiction of soft tissue structures, can enable superior visualization of the critical structures, often near lesions in the spine, including spinal nerve roots, vasculature, and spinal cord with surrounding cerebral spinal fluid (CSF), which can be well-visualized in comparison with the iceball treatment zone. Tumors typically have increased signal intensity on T2-weighted images, whereas iceballs cause a signal void; therefore, the coverage of the treatment zone in relation to the extent of tumor is normally easily depicted. MR imaging is ideal for tailoring the iceball treatment zone to cover as much of the lesion as possible without damaging nearby critical soft tissues. Because of these advantages, MR imaging-guided percutaneous cryotherapy for both soft tissue and bone spinal metastatic disease and primary tumors has been shown to be safe and feasible in anatomic locations adjacent to critical structures.¹²

Although there are inherent advantages of MR imaging as a guidance modality, there are also several disadvantages.⁷ There are fewer choices of MR imaging-compatible equipment and these often cost more than conventional equipment. MR imaging-guided procedures have the potential for being more time consuming and, therefore, more costly overall. However, faster imaging sequences with single images obtained on the order of 1 second and

the advancement of actual real-time monitoring systems of the needle position are helping to significantly reduce the time required for MR imaging–guided biopsies. In addition, there is a myriad of patient-specific contraindications to the MR imaging environment, including the presence of pacemakers or other non–MR imaging compatible medical devices or foreign bodies.

ANATOMY

MR imaging is often much better at depicting lesions and surrounding normal anatomic structures because of its superior contrast resolution and often superior spatial resolution compared with CT. Vessels are typically easily identified on most MR pulse sequences as are other critical structures, including nerve roots, thecal sac, CSF, and the spinal cord. Especially with biopsies of the spine, needle tip positions in the extradural, intradural/extramedullary, and intramedullary spaces can be readily identified on MR imaging sequences. Multiplanar two-dimensional MR imaging sequences and three-dimensional MR imaging sequences with multiplanar reformats provide high spatial resolution depiction of the anatomy in any desired imaging plane.

Similar to fluoroscopy- and CT-guided spine injections, the targets of MR imaging–guided spine injections include nerve roots, facet joints, and epidural space. Selective nerve root injections are performed with percutaneous transforaminal drug delivery into the spinal nerve sheath. Facet joint injection is performed with percutaneous injection of the drug into the lumbar facet joint space. Epidural injection is performed with percutaneous translaminar injection of the drug into the epidural space through a posterior intervertebral approach.³ Nontarget injection, including intravascular injection and injection into the subarachnoid space, is avoided with either real-time monitoring using fast MR imaging sequences or with aspiration before drug delivery.

IMAGING PROTOCOLS AND IMAGING FINDINGS

There has been a variety of MR imaging systems and configurations used for MR imaging–guided spinal interventions with greater emphasis now on the use of higher 3.0-T field strength systems. Higher-resolution spinal imaging and sequences with increased imaging speed are widely available on 3.0-T magnets. Wider-bore magnets (or typically lower field strength open-bore systems) allow for manipulation of the interventional equipment without moving the patient. After the initial high-resolution standard MR imaging sequences are obtained for lesion identification and planning, fast acquisition T1- or T2-weighted sequences are used for quick monitoring of needle advancement to the lesion of interest. If needed, specialized sequences that oversample the center of k-space (BLADE or PROPELLOR sequences) can be used to reduce patient motion artifact. In patients with spinal hardware, advanced MR imaging techniques, such as slice encoding for metal artifact correct and multiacquisition variable-resonance image combination, can be used to minimize metallic artifacts.¹³

MR imaging–guided spine interventions for low back pain have been performed in a few different MR imaging systems. In the past, MR imaging–guided spine interventions were

performed in dedicated open low-field-strength MR imaging systems.^{14–16} The low-field systems, however, had limited capability in providing real-time fluoroscopic guidance. More recently, a wide-bore high-field MR imaging system⁵ and an open high-field system with vertical field orientation¹⁷ have been used in spine interventions for low back pain. These novel high-field systems yield real-time or near real-time guidance and improved contrast-to-noise ratio.^{5,17}

Fritz and colleagues⁵ described the use of a 1.5-T open MR imaging system (Magnetom Espree, Siemens, Medical Solutions, Malvern, PA) with patients in prone position for different procedures including nerve root injection and facet joint injection (Figs. 1 and 2). For the diagnostic imaging phase of the procedure, this group used a body matrix coil with parallel imaging technology. The coil was then exchanged for a flexible loop coil for the interventional phase. Each procedure started with axial T1-weighted turbo spin echo imaging for planning of a needle path for direct access to target structures. For MR fluoroscopic determination of skin entry site, continuously acquired and displayed single-slice T1/T2*-weighted fast low angle shot (FLASH) two-dimensional MR imaging or T2-weighted fast imaging with steady-state precession was used as a syringe filled with saline solution or gadolinium-enhanced saline solution was moved over the skin. Following antiseptic preparation of the skin, draping, and induction of local anesthesia, the T1/T2*-weighted FLASH two-dimensional MR imaging sequence was used to navigate the puncture needle to the target structure with real-time MR imaging guidance. Injectants used in this study contained gadolinium-based contrast material. Following drug injection, T1-weighted imaging with fat suppression was performed for visualization of fluid distribution.

Fritz and colleagues⁵ also described the use of a 1.5-T open MR imaging system in guiding nonselective epidural injection in which injections were performed with the patient inside the bore and monitoring was continuously acquired and displayed as single-slice T1-weighted fast imaging with steady-state precession images (Fig. 3).

Streitparth and colleagues¹⁷ described the use of a 1.0-T open high-field MR imaging system (Panorama HFO, Philips, Best, Netherlands) for nerve root and facet injections. The system used was comprised of two horizontally opposed superconducting magnetic pole shoes with a distance of 40 cm between them creating a vertical static magnetic field. The patient was placed in the lateral position. A multipurpose loop coil was fixed to the back of the patient in an orthogonal position to B_0 . The intervention began with determination of the skin entry point using the finger-pointing technique. For localization of the target anatomy and subsequent near real-time needle guidance, proton density-weighted turbo spin echo imaging was exploited. Immediately before and after injection, heavily T2-weighted fat-saturated Spectral Presaturation with Inversion Recovery (SPIR) images were acquired to confirm injectant distribution.

Both of these groups demonstrated accuracy, safety, and efficiency of the aforementioned MR imaging-guided techniques for treatment of low back pain with no major complications reported. The duration of the procedure may be slightly longer, but the absence of radiation with these techniques makes them appealing, particularly for young patients or patients who require repetitive therapy. The real-time and near real-time sequences used by both groups

provide adequate anatomic delineation and acceptable, limited extent of needle-related artifact.

Another emerging application of MR imaging–guided treatment of chronic low back pain in a carefully selected group of patients is MR imaging–guided percutaneous cryotherapy of the facet joint. Cryodenervation was recently introduced as an alternative method for facet joint denervation for patients in whom lumbar zygapophyseal joints are a significant source of back pain.¹⁸ The lumbar facet joints are treated unilaterally or bilaterally when pain is distinctly localized and improves with facet drug injection. The therapeutic approach is based on using near real-time MR imaging guidance of the cryogenic probe toward the target lumbar facet joint. MR imaging allows accurate visualization of the growth of the cryogenic iceball and improves the accuracy of the treatment because the effect on the facet joint and surrounding tissues can be continuously monitored. However, currently, there are limited published studies on MR imaging–guided cryodenervation.

In addition to the MR imaging–guided spinal interventions for benign pathology described previously, we also present a variety of MR imaging–guided procedures involved in the diagnosis and treatment of pathologic conditions of the spine: fine-needle aspiration of an intrathecal nodule at the L1–L2 level, C1–C2 puncture with injection of intrathecal gadolinium to evaluate for spinal CSF leak, and cryoablation of L4–L5 posterior element metastatic disease.

INTRATHECAL NODULE BIOPSY

A 47-year-old woman presented with progressive cognitive deficits, diplopia, CN III palsy, and was noted to have scattered foci of leptomeningeal enhancement within the brain. Multiple lumbar punctures with CSF collection and an open neurosurgical biopsy of the dura overlying the frontal lobe were unrevealing, and therefore, a request was made for percutaneous biopsy of an approximately 1 cm focus of nodular enhancement at the conus medullaris (Fig. 4). Given this location, an MR imaging–guided percutaneous fine-needle aspiration was performed.

A flexible ring coil was placed over the lower back along with three gadolinium markers within the coil for initial imaging and selection of the skin entry point. A 16-gauge MR imaging–compatible introducer needle was advanced to the edge of the thecal sac at the level of the conus medullaris using a T1-weighted, three-dimensional gradient echo sequence, allowing for rapid acquisitions with high spatial resolution over the region of interest. Three 22-gauge MR imaging–compatible spinal needles were used serially in a coaxial fashion through the introducer needle to enter the thecal sac and obtain fine-needle aspiration biopsies from the conus nodule and obtain CSF for flow cytometry. Biopsy needle placement within the conus nodule was also confirmed using the rapid acquisition T1-weighted, three-dimensional gradient echo sequences. There were no complications on postbiopsy imaging. Flow cytometry from the samples obtained during the MR imaging–guided procedure were consistent with B-cell lymphoma.

C1–C2 PUNCTURE WITH INTRATHECAL GADOLINIUM INJECTION

A 41-year-old man presented with longstanding low-intracranial pressure headaches, exacerbated on standing, status post multiple epidural blood patches for presumed CSF leak that was not apparent on conventional CT myelogram. Given the patient's prior history of C6 corpectomy and small calcified disk protrusion at T1–T2, a lower cervical/upper thoracic level CSF leak was suspected. MR imaging–guided intrathecal gadolinium injection with C1–C2 puncture was considered the best option for detection of a small, heretofore undetected leak because it allows for the immediate imaging postinjection of intrathecal gadolinium and multiple rapid dynamic contrast-enhanced acquisitions following injection to evaluate for abnormal accumulation of extradural accumulation of gadolinium to identify the level of the CSF leak. Although this is an off-label use of gadolinium, MR myelography has been described in the literature¹⁹ and institutional review board approval was obtained for administration in this case.

With the patient in a left lateral decubitus position in the MR imaging scanner, a 22-gauge MR imaging–compatible spinal needle was advanced into the CSF space at the C1–C2 level using intermittent turbo spin echo T2-weighted sequences (Fig. 5). When CSF was returned, confirming the appropriate position, 0.5 mL of Magnevist (0.5 mol/L) diluted with 10 mL of sterile saline was injected. This was followed by the acquisition of multiple dynamic contrast-enhanced heavily T1-weighted sequences with the field of view covering the cervical and upper thoracic spine obtained every minute for 12 minutes following injection. These findings revealed an apparent subtle leak of contrast at the T1–T2 level. Subsequently, a CT-guided epidural blood patch targeted the T1–T2 level with partial relief of the patient's symptoms.

CRYOABLATION OF SPINAL METASTATIC DISEASE

A 68-year-old man with a history of metastatic prostate cancer and diffuse large B-cell lymphoma was found to have a new mass eroding the right L4 lamina and right L4–L5 facet joint. To prevent spinal canal compromise and instability at this level, MR imaging–guided cryoablation was considered the most appropriate treatment in this nonsurgical candidate.

After the patient was placed under general anesthesia, he was positioned prone on the MR imaging table. Preliminary imaging was obtained to confirm the target and to determine the approach. Initially, a 16-gauge MR imaging–compatible introducer was placed along the right paraspinal area at the L4–L5 level under MR imaging guidance. Fine-needle aspiration biopsies using 22-gauge MR imaging–compatible Chiba needles were obtained in a coaxial fashion under MR imaging guidance to ensure targeting of the lesion. Core biopsy samples were obtained coaxially using an 18-gauge MR imaging–compatible core biopsy needle.

Using MR imaging guidance (Fig. 6), two 17-gauge cryoprobes were placed into either side of the mass. With frequent MR imaging monitoring, using turbo spin echo T2-weighted sequences to ensure the iceballs encompassed the mass but did not involve the CSF, alternating cycles of freezing and thawing were performed as follows: 15-minute freeze, followed by 10-minute passive thawing, followed by 15-minute freeze, then 3-minute active

thawing. The second cycle of freezing was performed at 100%, then decreased to 40% at 7 minutes, then 20% at 10 minutes. Following the active thaw, the cryoprobes were removed without complication. On subsequent follow-up, the patient reported improvement in his pain without evidence of complication. The subsequent follow-up PET/CT studies showed there was complete resolution of fluorodeoxyglucose activity of the lesion and no further thinning of the lamina or epidural extension.

PEARLS, PITFALLS, AND VARIANTS

MR imaging fluoroscopic imaging used during needle placement needs to provide good imaging contrast and produce sharp and symmetric needle artifacts to achieve improved accuracy and safety. Different imaging protocols exist, including gradient echo and turbo spin echo sequences. Adequate needle visualization is important for preventing complications, including bleeding, dural puncture, spinal anesthesia, neural trauma, hematoma formation, and steroid side effects.²⁰

Detection of intravascular location of the needle is crucial to avoid nontarget drug injection and ensure drug delivery to the target. Aspiration should be performed before drug injection to detect intravascular needle location. Continuous monitoring of injection with real-time MR imaging may improve sensitivity in detecting vascular uptake.^{21,22}

Monitoring of drug distribution following injection is commonly performed to ensure target injection and detect injection into nontargeted structures. This is performed with fat-saturated T1-weighted imaging if the injectant contains gadolinium-based contrast material or with T2-weighted sequence if contrast material is not used.

MR imaging–guided spinal interventions are also available for the diagnosis and treatment of different spinal pathologies, including primary and metastatic soft tissue and bony lesions of the spine. Because of the superior contrast resolution and spatial resolution offered by MR imaging, it is often ideal as a guidance modality to avoid critical structures adjacent to the targeted lesion.

MR imaging–guided cryotherapy of soft tissue and bony metastatic disease has the ability to obtain local tumor control and pain relief in patients who have often exhausted other treatment options. Cryotherapy is far less likely to harm major blood vessels and CSF because of the warm flow within these structures; has inherent pain alleviation effects immediately postprocedure unlike other ablation techniques, such as radiofrequency ablation; and provides a sharply demarcated zone of treatment.

INFORMATION THE REFERRING PHYSICIAN NEEDS TO KNOW

The availability of MR imaging–guided spine interventions for back pain is currently limited, but interest and expertise are growing. With ongoing advancements in MR imaging techniques, new applications emerge. MR imaging–guided injections of the nerve root, facet joint, and epidural space have been successfully performed.

MR imaging–guided interventions for back pain can be beneficial because of superior visualization of soft tissues and fluid, and absence of exposure to ionizing radiation. MR imaging–guided interventions for diagnosis and treatment of soft tissue and bony spinal lesions are safe and effective because they provide superior visualization of soft tissues and fluid, can avoid injury to adjacent critical structures, and provide absence of exposure to ionizing radiation.

The current availability of MR imaging–guided spine interventions for diagnosis and treatment of spinal lesions continues to be limited because of the equipment costs and lack of universal expertise. However, in the near future, it will probably play an increasing role as it currently does in treatment of solid organ masses. In particular, cryoablation for local tumor control and pain relief in spinal metastatic disease seems to be one of the more appropriate applications.

SUMMARY

MR imaging–guided interventions for treatment of low back pain and for diagnosis and treatment of soft tissue and bony spinal lesions have been shown to be feasible, effective, and safe. Several advantages of this emerging technique include the absence of ionizing radiation, the high tissue contrast, and multiplanar imaging options. Recent advancements in MR imaging systems allow improved image quality and real-time guidance. MR imaging–guided cryotherapy of spinal metastatic disease shows special promise for local tumor control and pain relief in appropriately chosen patients.

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KEY POINTS

- The availability of MR imaging–guided spine interventions for back pain is currently limited, but interest and expertise are growing.
- MR imaging–guided interventions for back pain can be beneficial because of superior visualization of soft tissues and fluid, and absence of exposure to ionizing radiation.
- MR imaging–guided interventions for diagnosis and treatment of soft tissue and bony spinal lesions are safe and effective because of their superior visualization of soft tissues and fluid enabling avoidance of injury to adjacent critical structures and absence of exposure to ionizing radiation.
- The availability of MR imaging–guided spine interventions for diagnosis and treatment of spinal lesions currently continues to be limited because of the equipment costs and lack of universal expertise.
- These costs will probably play an increasing role in the future for treatment of solid organ masses.

Fig. 1.

MR imaging-guided steroid injection of nerve root. (A) Axial T1-weighted turbo spin echo MR image shows planned needle path (*long arrow*) to left L4 nerve root (*short arrow*). (B) Fast low angle shot (FLASH) two-dimensional MR imaging allows real-time visualization during placement of needle (*arrow*) to nerve root. (C) Axial fat-saturated T1-weighted turbo spin echo MR image after injection of 3 mL of steroid and gadolinium-based contrast mixture shows injectant (*white arrow*) in circumneural sheath of spinal nerves and in epidural space (*black arrow*). (From Fritz J, Thomas C, Clasen S, et al. Freehand real-time MRI-guided lumbar spinal injection procedures at 1.5 T: feasibility, accuracy, and safety. *AJR Am J Roentgenol* 2009;192:W163; with permission.)

Fig. 2.

MR imaging-guided injection of steroid into lumbar facet joint. (A) Axial T1-weighted turbo spin echo MR image shows planned needle path (*long arrow*) for steroid injection of the right L4–L5 facet joint (*short arrow*). (B) FLASH two-dimensional MR imaging allows real-time visualization during advancement of needle (*arrow*) to facet joint. (C) Axial fat-saturated T1-weighted turbo spin echo MR image acquired after injection of 0.8 mL of steroid and gadolinium-based contrast mixture demonstrates injectant (*arrow*) in joint space. (From Fritz J, Thomas C, Clasen S, et al. Freehand real-time MRI-guided lumbar spinal injection procedures at 1.5 T: feasibility, accuracy, and safety. *AJR Am J Roentgenol* 2009;192:W164; with permission.)

Fig. 3. MR imaging-guided steroid epidural injection for nonspecific lower back pain. (A) Axial T1-weighted turbo spin echo MR image shows planned needle path (*arrow*) into epidural space. (B) FLASH two-dimensional MR imaging allows real-time visualization during needle (*arrow*) advancement into epidural space. (C) Axial T1-weighted real-time fast imaging with steady-state precession shows distribution of steroid and gadolinium-based contrast mixture (*arrow*) in epidural space. (From Fritz J, Thomas C, Clasen S, et al. Freehand real-time MRI-guided lumbar spinal injection procedures at 1.5 T: feasibility, accuracy, and safety. *AJR Am J Roentgenol* 2009;192:W165; with permission.)

Fig. 4.

Intrathecal nodule biopsy. Planning sequences including a T2-weighted sagittal sequence (A) and a T1-weighted postcontrast axial sequence (B) demonstrated a T2 hypointense, enhancing 1-cm nodule (arrow) involving the conus medullaris at the level of the inferior endplate of L1. A turbo spin echo sagittal T2-weighted sequence (C) shows the introducer needle (arrowhead) with coaxial biopsy needle entering into the intrathecal nodule (arrow). An axial T1-weighted three-dimensional gradient echo sequence (D) demonstrates introduction of the biopsy needle in coaxial fashion through the introducer needle targeting the intrathecal nodule.

Fig. 5.

MR imaging-guided intrathecal injection of gadolinium for evaluation of CSF leak. (A) An axial T2-weighted sequence shows the signal void from the spinal needle (*arrowhead*) entering into the CSF space at the C1–C2 level. Multiplanar rapid acquisition dynamic contrast-enhanced T1-weighted sequences were obtained every 1 minute postinjection to evaluate for CSF leak. (B) Coronal acquisition in one of the later phases. (C) A subtle extradural collection of gadolinium is seen along the dorsal aspect of the thecal sac at the T1–T2 level (*arrow*).

Fig. 6.

Cryoablation of metastatic spinal disease. Axial turbo spin echo T2-weighted sequence (*A*) shows the placement of two cryoprobes (*arrowheads*) at either side of the lesion at the right L4 lamina bordering the right L4–L5 facet joint. During a maximal freeze period, the iceball (*arrows*) can be seen in relation to the surrounding structures and adjacent CSF and cauda equina nerve roots (*B, C*), ensuring coverage of the lesion without subsequent freezing of these adjacent structures. Fused axial image of the PET-CT study before the cryoablation (*D*) shows the lesion to be highly fluorodeoxyglucose avid, with follow-up PET 6 months

following the procedure (*E*) showing near complete resolution of the fluorodeoxyglucose avidity at the treatment site.

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