Interventional Magnetic Resonance Imaging: Current Concepts, Enabling Technologies, and Emerging Clinical Applications

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Abstract

Interventional magnetic resonance imaging (iMRI) has evolved from an experimental imaging platform into an established modality for guiding minimally invasive diagnostic and therapeutic procedures. Its unique combination of superior soft tissue contrast, multiplanar imaging, real time guidance, and absence of ionizing radiation provides decisive advantages over conventional image guidance techniques. Despite these strengths, the adoption of iMRI has historically been constrained by technical complexity, cost, and workflow challenges.

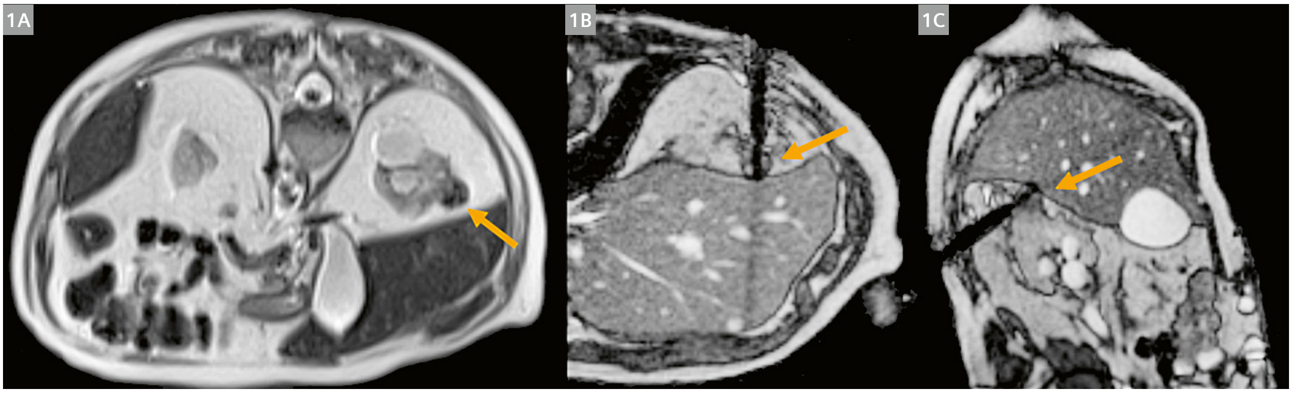
Recent advances, including renewed interest in lower field MRI systems and the maturation of MRI guided ablation techniques such as cryoablation and transurethral ultrasound ablation (TULSA) for prostate, are reshaping the field.

This narrative review summarizes the fundamental principles of iMRI, discusses how lower field MRI units may facilitate wider adoption, and reviews contemporary clinical applications with a focus on MRI guided biopsy, cryoablation, TULSA for prostate, and endovascular procedures.

Introduction

Magnetic resonance imaging (MRI) is widely regarded as the reference standard for soft tissue imaging owing to its excellent contrast resolution, multiplanar capability, and lack of ionizing radiation. Although initially limited to diagnostic use, MRI has progressively expanded into the interventional domain over the past three decades. Interventional MRI (iMRI) refers to diagnostic or therapeutic procedures performed under MRI guidance, using MRI for lesion localization, device navigation, intraprocedural monitoring, and immediate post treatment assessment.

Early iMRI procedures were performed in the 1990s using open, low field MRI systems that allowed direct access to the patient but were limited by poor image quality. The subsequent introduction of wide bore, high field MRI scanners, MRI compatible devices, and fast imaging sequences enabled more complex interventions, including biopsies and tumor ablation. Among these, MRI guided cryoablation has become a cornerstone application because of its inherent compatibility with MRI physics and the ability to directly visualize treatment effects [1]. This



1 A 79-year-old male patient presenting with an exophytic nodule arising from the upper pole of the right kidney. **(1A)** Axial T2-weighted MR image demonstrates the target lesion (arrow). The patient subsequently underwent percutaneous MRI-guided biopsy. **(1B)** Axial and **(1C)** sagittal BEAT MR images show the biopsy needle sampling the target renal nodule.

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Rationale and advantages of interventional MRI

Compared with computed tomography (CT), fluoroscopy, and ultrasound, iMRI offers several unique advantages:

- Superior soft tissue contrast enabling precise lesion delineation
- Multiplanar imaging without patient repositioning
- Near real time guidance during device advancement
- Intraprocedural assessment of tissue response
- Absence of ionizing radiation for patients and staff
- Possibility to allow temperature monitoring during thermal ablation procedures

These characteristics are particularly valuable when lesions are not visible on other imaging modalities, when anatomy is complex, or when adjacent critical structures must be preserved [1, 2].

MRI systems for interventional use

High field closed bore MRI systems

Most contemporary iMRI procedures are performed in wide, closed bore 1.5T to 3T scanners. These units provide high signal to noise ratios, advanced pulse sequences, and robust workflow integration. However, a closed bore geometry limits operator ergonomics and physical access to the patient, and the associated costs and infrastructure requirements may restrict iMRI availability on a large sale.

Lower field MRI systems: Facilitating adoption

Lower field MRI systems (≤ 1T), historically regarded as obsolete, have gained renewed interest due to improvements in magnet design, radiofrequency coils, and image reconstruction. Moreover, image quality has been significantly improved thanks to artificial-intelligence-based algorithms, and now equals that obtained with high field systems. Accordingly, modern lower field MRI may be sufficient for many interventional tasks.

Importantly, lower field systems may facilitate broader adoption of iMRI by lowering costs, simplifying siting requirements, improving ergonomics, and reducing susceptibility artifacts. These advantages are particularly relevant for intraoperative and point of care interventions and may enable dissemination of iMRI beyond tertiary academic centers [3, 4].

MRI compatible devices and imaging techniques

iMRI requires the use of non ferromagnetic, MRI compatible needles, probes, and catheters. Device visualization relies primarily on susceptibility artifacts rather than direct depiction of the device shaft. Artifact size increases with magnetic field strength and varies with device orientation relative to the main magnetic field, which may complicate interpretation when multiple instruments are used simultaneously.

Commonly used imaging sequences include fast T2 weighted sequences (HASTE, BLADE) for lesion visualization, balanced steady state free precession sequences for MR fluoroscopy, and MR thermometry for heat based therapies [1].

MRI guided biopsy

MRI guided biopsy is an essential diagnostic application of iMRI for lesions that are poorly visible or inaccessible under ultrasound or CT guidance. MRI guided biopsies are performed using MRI compatible needles, often with a coaxial technique, and may be combined with ablation in the same session. MRI allows direct targeting of lesions visualized on diagnostic MRI, including diffusion restricted or contrast enhancing foci [1].

The retro orbital compartment presents a challenging biopsy environment due to confined anatomy and proximity to the optic nerve and vascular structures. MRI guided biopsy offers superior safety and accuracy in selected cases, particularly for lymphoproliferative, inflammatory, or metastatic lesions [2].

MRI guided biopsy is also often useful for renal (Fig. 1) and hepatic lesions visible only on MRI and for deep seated lymphadenopathies adjacent to critical structures. MRI guidance enables accurate needle placement while minimizing radiation exposure and improving diagnostic yield in complex cases [1, 2].

MRI guided cryoablation

MRI guided cryoablation is one of the most mature and widely applied therapeutic applications of iMRI. Cryoablation induces tissue necrosis through repeated freeze–thaw cycles, resulting in cell membrane disruption, microvascular thrombosis, and delayed ischemic injury. A defining advantage of cryoablation under MRI guidance is the direct visualization of the ice ball, which appears as a sharply demarcated signal void on all MRI sequences [1].

Small renal masses are a well established indication for MRI guided cryoablation, particularly in patients with significant comorbidities, limited renal reserve, a solitary kidney, or hereditary renal tumor syndromes. MRI guidance is especially valuable for lesions that are isoattenuating on CT.

MRI allows precise monitoring of ice ball expansion relative to the renal collecting system, adrenal gland, bowel, pancreas, and adjacent nerves. Hydrodissection is frequently used and readily visualized under MRI. Clinical studies have demonstrated high technical success, favorable oncologic outcomes, and preservation of renal function in appropriately selected patients [1, 5–7].

Desmoid tumors are benign but locally aggressive fibroblastic neoplasms with high recurrence rates after surgery. MRI guided cryoablation has emerged as a minimally invasive alternative, allowing tailored debulking or curative ablation while avoiding surgical trauma. Large studies report high rates of symptomatic relief and functional improvement with low complication rates [8].

Abdominal wall endometriosis is another emerging clinical field for MRI-guided cryoablation (Fig. 2). Often occurring after cesarean section or laparoscopic surgery, abdominal wall endometriosis may cause chronic pain and inflammation. MRI guided cryoablation enables precise targeting of endometriotic implants while preserving surrounding musculature and fascia. Early experience suggests durable pain relief and minimal morbidity compared with surgical excision [1].

Additional soft tissue applications include Morton's neuroma, peripheral-nerve related pain syndromes, in transit melanoma metastases, and selected vascular malformations, where MRI guidance provides decisive anatomic definition and cryoablation ensures controlled tissue destruction [1, 9].

MRI guided transurethral ultrasound ablation

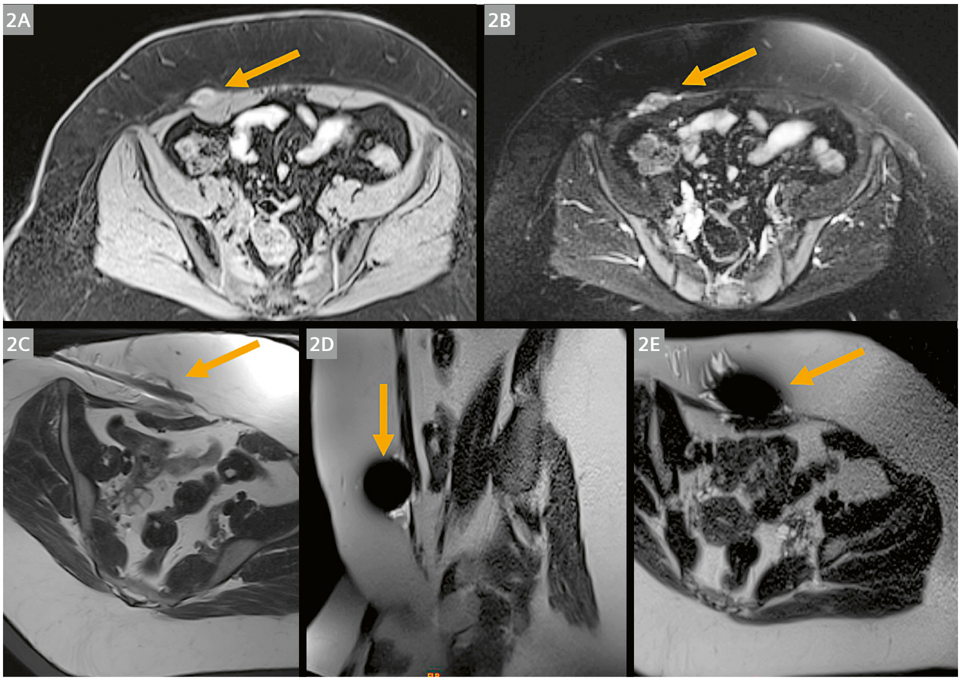
Transurethral ultrasound ablation (TULSA) is an incision free, MRI guided therapy for localized prostate cancer and benign prostatic hyperplasia. Ultrasound energy is delivered via a transurethral applicator, while MRI provides real time anatomic visualization and thermometry, enabling closed loop temperature control.

Clinical studies have demonstrated a favorable safety profile, preservation of urinary continence and erectile function, and meaningful oncologic control in selected patients. However, residual or recurrent clinically significant disease has been reported, underscoring the need for careful patient selection and follow up [6, 7, 10].

Endovascular applications of interventional MRI

Endovascular interventional MRI is one of the most technically demanding yet conceptually promising extensions of iMRI. While contemporary endovascular procedures are almost exclusively performed under X ray fluoroscopic guidance, MRI offers unique advantages, including the ability to acquire functional and flow sensitive information.

Reported applications include arterial catheter navigation, targeted embolization, and preclinical and early clinical feasibility studies involving aortic, peripheral, visceral, and neurovascular interventions. However, clinical adoption remains limited by technical challenges such as reduced temporal and spatial resolution compared with



2 A 30-year-old female patient presenting with a painful endometriotic implant in the right anterior abdominal wall.
(2A) Axial T1-weighted and **(2B)** axial T2-weighted MR images demonstrate the target lesion (arrows). The patient subsequently underwent percutaneous MRI-guided cryoablation.
(2C) Axial T2-weighted MR image shows one of the two cryoprobes (arrow) positioned within the lesion.
(2D) Sagittal and **(2E)** axial T2-weighted MR images demonstrate the ice ball (arrows) completely encompassing the target lesion during cryoablation.

fluoroscopy, device visualization and tracking constraints, radiofrequency induced heating, and the limited availability of dedicated MRI compatible guidewires and catheters.

Recent advances in passive and active catheter tracking, MR safe endovascular devices, and optimized real time MRI sequences have significantly advanced the field. Systematic reviews and expert analyses indicate that MRI guided endovascular interventions are feasible and safe in selected experimental and early clinical settings, although current human experience remains limited to small case studies. Continued technological development, including integration with lower field MRI platforms, may be critical for broader clinical translation of MRI guided endovascular therapies [11–13].

Future perspectives and conclusion

Interventional MRI represents a powerful convergence of imaging and minimally invasive therapy. Advances in lower field MRI technology, growing clinical evidence for MRI guided cryoablation and TULSA, and increasing experience with MRI guided biopsy are accelerating the clinical integration of iMRI. As technology and expertise evolve, iMRI is poised to become a central platform for precision guided interventions across oncologic, musculoskeletal, and functional domains.

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