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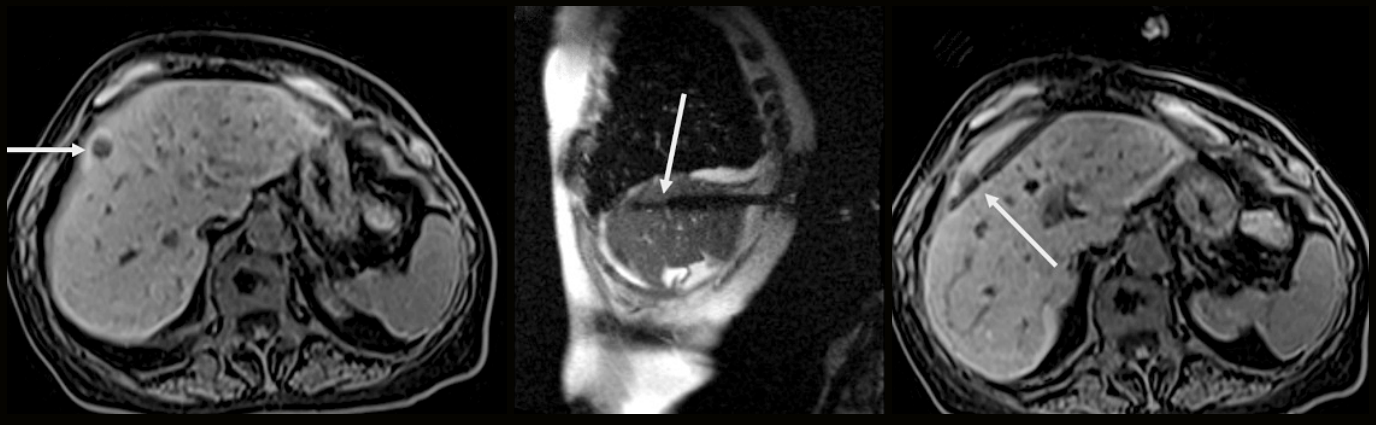
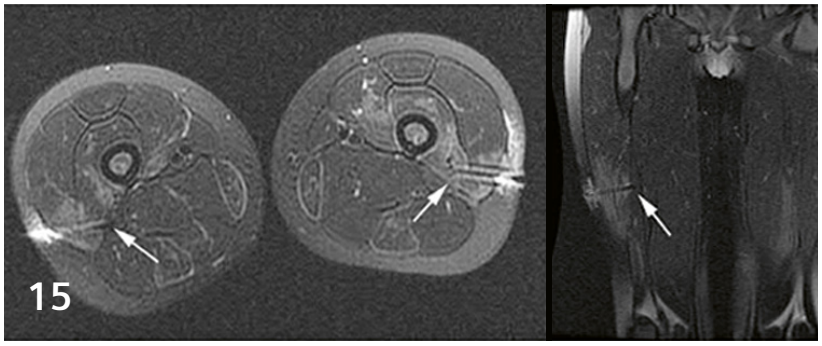
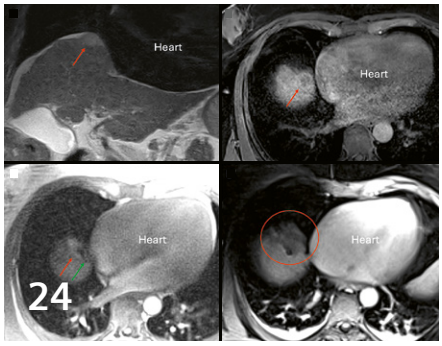




MRI of the needle position in the vastus lateralis



Ablation of a liver lesion next to the heart

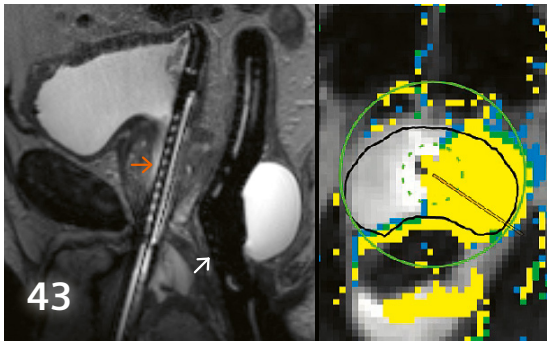
Spotlight

Editorial Comment

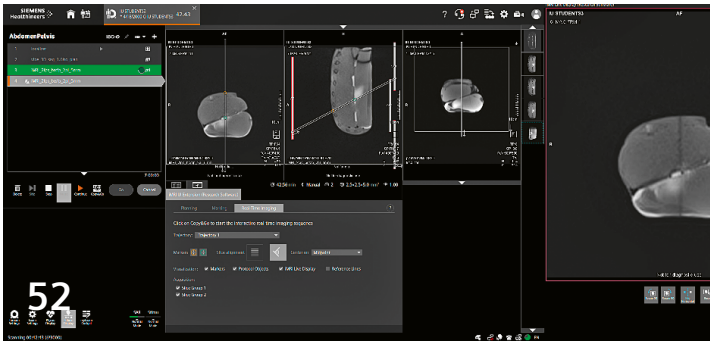
Interventional MRI

Hepatic iMRI

[1] *The iMRI UI Extension is work in progress. The product is still under development and not commercially available. Its future availability cannot be ensured.*



Transurethral ultrasound ablation

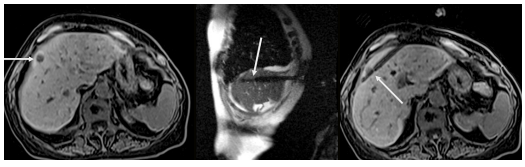


The interactive real-time imaging user interface[1]

Urologic iMRI

How I do it

Meet Siemens Healthineers



Cover:
Cover images from *Establishing an MRI-Guided Intervention Service Using a 0.55T System* by JR Kroeger and S Saeed (Johannes Wesling Klinikum Minden, Germany).

iMRI in Practice: Expert Voices from Clinical Routine

Interventional MRI (iMRI) is emerging as a transformative response to longstanding unmet clinical needs. Offering real-time, radiation-free imaging with excellent soft tissue contrast, iMRI enables precise targeting and minimal invasiveness across a growing range of procedures. Its seamless integration into clinical workflows simplifies complex interventions, while supporting more personalized patient care. As iMRI transitions from innovation to routine, it is changing the landscape of everyday medical practice – from diagnosis to treatment and beyond.

"Interventional MRI allows for precision anatomic targeting that is essential to providing truly personalized medicine. As the technology continues to evolve, we will see MRI-guided interventions shifting from a "problem-solving tool" to a mainstay of modern clinical care."

Clifford R. Weiss, M.D., FSIR, FCIRSE
Professor of Radiology and Radiological Science, Johns Hopkins Medicine

"iMRI has entered into clinical routine at our facility and means an epic change for biopsy and treatment of liver tumors."

Max Seidensticker, M.D.
Professor of Radiological Image Guidance in Minimally-Invasive Oncology, LMU Hospital

"iMRI is a game-changer for clinical care, from brain tumor resection to prostate cancer diagnosis and treatment. Patients travel from all over to receive care with iMRI."

Clare M. C. Tempany-Afdhal, M.D., MB BAO BCh
Vice-Chair of Radiology Research, Brigham and Women's Hospital

"Interventional MRI: pinpoint precision, tiny incisions, faster healing."

Jurgen Fütterer, Ph.D.
Professor of Image-Guided Oncological Interventions at the Faculty of Medical Sciences, Radboud University

"Seeing better means treating better, and that's what iMRI is all about. And the cherry on top: no radiation. That's why iMRI has been part of the routine at our center since 2007."

Afshin Gangi, M.D., Ph.D.
Professor and Chairman, Radiology and Nuclear Medicine Department, University Hospitals of Strasbourg

"iMRI combines real-time imaging with precision medicine for safer and more effective treatments with better outcomes for our patients."

Frank Wacker, M.D.
Professor and Chairman, Department of Radiology, Hannover Medical School

"Interventional MRI: At last, a near real-time imaging/procedural modality which mirrors the "surgeons view" without the morbidity of an incision."

Lance A. Mynderse, M.D., MS, FACS
Associate Professor of Radiology and Urology, Mayo Foundation for Medical Education and Research

"Interventional MRI is reaching a tipping point, moving from a niche technology to a mainstream tool for radiologists – delivering a new standard of care for patients everywhere."

Jan-Robert Kröger, M.D., EBIR
Managing Senior Physician at Johannes Wesling Klinikum Minden

"iMRI addresses an unmet clinical need and capitalizes on the interventionalist's skillsets, including imaging, diagnostics, guidance, and therapy, all in one. This represents the future of interventions."

Riad Salem, M.D.
Professor of Radiology, Medicine, and Surgery, Northwestern University

"For us, interventional MRI provides the platform for our mission, which is to create hope where there is none, by creating new procedures where none existed."

David A. Woodrum, M.D., Ph.D.
Assistant Professor of Interventional Radiology, Mayo Clinic Rochester

Associate Professor David A. Woodrum, M.D., Ph.D. is a board-certified radiologist with advanced fellowship training in Interventional Radiology and MR Imaging from the Mayo School of Graduate Medical Education at the Mayo Clinic College of Medicine. He completed his residency in Diagnostic Radiology, as well as a preliminary residency in Internal Medicine, through programs in Rochester at the same institution. Prior to his specialty training, he completed an internship in Internal Medicine at Mayo Clinic.

Dr. Woodrum researches the molecular cell signaling mechanisms of tumor resistance to thermal ablation and new techniques for MRI-guided thermal ablation. His specialty is interventional radiology, with an emphasis on oncology treatment and MRI interventions. He has a background in physics, cellular biology and interventional radiology.

MRI: The Next Frontier in Interventional Radiology

Interventional radiology (IR) has always centered on delivering precision medicine through targeted therapy using the most accurate imaging guidance with the least invasive techniques. Over the past 15 years, I have seen a translation of IR procedures from fluoroscopy-based guidance to the incorporation of ultrasound and CT in a bid to enhance the precision of guidance for the procedures being performed. MRI guidance for procedures offers the next frontier in imaging guidance, with unprecedented lesion conspicuity and treatment monitoring capabilities. In my own clinical practice, MRI has continually enhanced or created the image-guidance platform to enable procedures that were extremely difficult or even impossible with other imaging platforms. What began as a small number of exploratory MRI-guided procedures performed off-hours has evolved into a high-volume, multidisciplinary interventional MRI (iMRI) program encompassing hepatic, prostatic, renal, and musculoskeletal procedures [1].

A personal perspective on the evolution of MRI guidance

This editorial offers a personal perspective on that evolution, written from the viewpoint of a clinician who performs MRI-guided interventions on a near-daily basis. MRI fundamentally changes how one approaches procedural targeting and monitoring. The proceduralist quickly recognizes the fact that if you can see it, then you can target it. Additionally, if you can precisely see what is happening from a treatment/ablation standpoint, then you can quickly tailor your approach to maximize treatment effect while minimizing collateral damage. If we can target and monitor very accurately, then we can treat more precisely with a minimal side-effect profile. This is and always has been the IR mentality. MRI becomes the next tool to advance this philosophy. What previously felt like limitations, such as blurred lesion margins on CT, invisible targets under ultrasound, or repeated needle repositioning, now appear as unnecessary compromises. MRI guidance not only offers superior targeting and monitoring, but with innovative integration with ultrasound and fluoroscopy, it offers the possibility of a “true” multimodality procedure suite which delivers on making the impossible possible for the patient.

Expanding the clinical scope of iMRI

We initially focused on MRI-guided biopsies of lesions that were poorly visualized on CT or ultrasound, particularly in the liver and pelvis. However, we quickly expanded to recurrent prostate cancer after surgery and/or radiation, due to limited treatment options for these patients. This

represented an expansion driven by clinical need, which is what exemplifies the driving force behind the use of MRI guidance. MRI guidance is not replacing US or CT guidance; rather, it is creating procedures which did not exist or were not feasible previously.

As our confidence and operational efficiency grew, we broadened the scope of our procedures to include a full spectrum of thermal ablations (i.e., laser, microwave, and focused ultrasound) and complex interventions requiring precise targeting (i.e., at the scale of a few millimeters) and monitoring secondary to associated collateral sensitive structures. We have successfully guided cryoablation probes into renal tumors adjacent to the bowel, treated centrally located hepatocellular carcinomas with millimetric precision, and performed prostate ablations with submillimeter accuracy, all under real-time MRI visualization.

Precision targeting in prostate and liver interventions

Among the organs we treat, prostate and liver are the most common. In the prostate, MRI is essential for diagnosis in native and recurrent disease. It is therefore a logical conclusion that we would need MRI guidance for the most precise targeting and monitoring of treatment. In the liver, MRI is recognized as the most sensitive imaging platform for the diagnosis of liver lesions. However, with MRI-guided intervention, we no longer must wait for the 3–5 mm lesions to get bigger for biopsy or intervention. We can accurately target and treat these lesions while they are still tiny, potentially impacting the overall progression. While CT continues to play a valuable role for lesions > 1 cm, MRI opens up a new range of treatment options in the < 1 cm category. Additionally, the MRI monitoring capabilities are essential in the prostate, where we are trying to preserve urethra and nerve bundles as well as ureters, bladder wall, and rectum. Working in the confined region of the pelvis with so many immediately adjacent structures that must be preserved has driven the need for MRI guidance for targeting and, more importantly, for monitoring the ablation treatment. In the liver, the importance of monitoring is driven by the need for accurate marginal coverage of the target lesion, especially with the negatively competing vasculature, and by the need to monitor adjacent structures such as bowel, gallbladder, and heart. These capabilities offer the possibility of new patient treatment options with fewer side effects and better outcomes. A recent comparative study of CT-guided versus MRI-guided liver biopsies for focal lesions under 2 cm reinforced what many of us observe in clinical practice: MRI-guided interventions achieved higher diagnostic yield, smaller mean lesion size, and fewer complications, thus highlighting their suitability for high-risk, high-precision cases. These results underscore the clinical added value of MRI in procedural medicine, especially in oncology, where lesion conspicuity and precision are paramount [2].

Overcoming barriers to adoption

However, broader adoption of iMRI still faces barriers. In many centers, MRI continues to be viewed primarily as a diagnostic resource, and logistical challenges (scanner access, team training, MR safety, and lack of interventional protocols) can hinder progress, as shown in the past. This is where recent technological innovations play a pivotal role.

Reimbursement: A critical piece of the puzzle

Reimbursement is an essential part of any procedure. As we look to expand the role of MRI guidance, this must be acknowledged and tackled. Currently, many iMRI procedures fall into ambiguous or under-recognized billing categories, which can disincentivize their use despite the strong clinical evidence, especially when viewed in competition with well-recognized diagnostic reimbursement codes. More dedicated MR procedural codes are necessary, and making these changes will require a combined approach from corporate partners, physician proceduralists, and national medical societies. Clearer procedural coding and appropriate reimbursement models that align with the actual clinical effort, equipment, and infrastructure involved will be essential to support the adoption of iMRI on a broader scale. As more data on outcomes emerge, particularly regarding complication rates, patient safety, and long-term cost savings (e.g., fewer repeat procedures or hospital readmissions), the case for reimbursement reform becomes even stronger.

The role of MRI in surgical settings

Beyond percutaneous interventions, MRI is increasingly being incorporated into surgical settings in the brain and, more recently, in complex pelvic tumors. Urologic surgeons are utilizing MRI guidance for resections and intraoperative margin assessments, particularly in complex pelvic tumors [3]. Looking ahead, this pattern will likely continue as MRI will become more deeply integrated, offering real-time image guidance during resection and reconstruction to make the surgical procedures even better than they are currently. The underlying technology exists; the next step

is to refine the workflow and achieve broader clinical adoption. None of this is possible without multidisciplinary collaboration, as iMRI relies on tightly coordinated teams of radiologists, technologists, anesthesiologists, and nursing staff. Institutional support is essential, particularly in areas such as equipment acquisition, procedure scheduling, and reimbursement infrastructure. However, once these foundational elements are in place, the clinical benefits of iMRI become clear and difficult to overlook. In our department, iMRI is no longer viewed as an experimental or niche capability; it is an essential part of our clinical interventional oncology practice and it continues to grow.

The rise of low-field MRI systems

The introduction of low-field MRI systems, particularly 0.55T, is facilitating a fundamental shift. These systems are enabling greater technological integration and allowing more conventional interventional workflows. They offer easier adoption across the board and provide wide bores, improved patient access, and lower infrastructure costs. Most importantly, the image quality for procedural guidance is comparable to that of 1.5T, particularly when using modern image reconstruction techniques enhanced with AI technology. Continued evolution of the imaging capabilities at lower field (0.55T) is essential for providing sufficient spatial and contrast resolution for targeting and real-time monitoring, even in technically demanding cases. All of this together makes 0.55T MRI an ideal platform for institutions looking to establish or scale iMRI services without disrupting diagnostic throughput.

Industry collaboration and technological integration

The growing availability of MRI-compatible interventional tools, from ablation applicators to biopsy devices and guidance systems, is addressing a key practical limitation. Industry collaborations are accelerating progress in this area. The strategic partnership between Siemens Healthineers and Cook Medical, for instance, is focused on codeveloping MR-compatible procedural devices and seamless workflows that support safe, efficient, and reproducible interventions. This type of alignment between imaging technology and therapeutic tools is critical for transforming iMRI into a scalable and sustainable clinical solution.

Starting an iMRI program: Practical recommendations

For colleagues and institutions considering the integration of iMRI into their practice, my recommendations are straightforward:

1. Start with a clear need for MRI with the lesions that are difficult to visualize on CT or ultrasound for biopsy and/or ablation.
2. Consider patients for whom repeated radiation exposure is a concern.
3. Train a specialized team of MR technicians, nurses, and physicians to maximize procedural success and safety. Although there are fewer safety constraints with lower-field MRI (0.55T), they are still omnipresent within the MRI suite.

With the appropriate tools and infrastructure, it becomes readily apparent that MRI does not merely assist with image guidance; it transforms it. We are entering a new chapter in image-guided and radiation-free therapy, and MRI is central to that evolution. It offers the precision we have always sought, the safety our patients increasingly expect, and the procedural control necessary to deliver the best-possible outcomes. For those of us already performing a high volume of iMRI-guided interventions, this is no longer an emerging technology. It is the new standard we hold ourselves to today.

David Woodrum

References

1 Thompson SM, Gorny KR, Koepsel EMK, Welch BT, Mynderse L, Lu A, et al. Body Interventional MRI for Diagnostic and Interventional Radiologists: Current Practice and Future Prospects. Radiographics. 2021;41(6):1785–1801.
2 Schmidt VF, Öcal O, Walther V, Fabritius MP, Dietrich O, Kazmierczak PM, et al. Clinical benefits of MRI-guided freehand biopsy of small focal liver lesions in comparison to CT guidance. Eur Radiol. 2024;34(9):5507–5516.
3 van Luijtelaar A, Fütterer JJ, Bomers JG. Minimally invasive magnetic resonance image-guided prostate interventions. Br J Radiol. 2022;95(1131):20210698.

Interventional MRI: Emerging Innovations and Clinical Frontiers

Arun Kamireddy, MBBS[1]; Mohammad Mirza Aghazadeh Attari, M.D.[1]; Clare Tempany-Afdhal, M.D.[2]; Clifford R Weiss, M.D.[1]

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Interventional MRI (iMRI) is a standard approach used by multidisciplinary teams of doctors across the globe. It allows physicians to use MR images to plan, guide, navigate, and deliver therapy simultaneously and often in real time. This innovation dates back over 20 years to early pioneers such as Ferenc Jolesz, Peter Black, Dietrich Groenemeyer, and Ron Kikinis, to name just a few. As the field advanced, it became very evident that a specialized scientific meeting focused on this subject was required and highly desired by all practitioners of MRI-guided interventions. Thus, in 1996, the Interventional MRI Society was co-founded by three pioneers and leaders in the field:

1 Members of the Interventional MRI Society. From left to right, in front: Ferenc Jolesz, M.D.; Jon Lewin, M.D.; Thomas Kahn, M.D.; in back: John Carrino, M.D.

Ferenc Jolesz, M.D., Jonathan Lewin, M.D., and Thomas Kahn, M.D. (Fig. 1).

Jolesz, regarded today as the father of MRI-guided interventions, was a Hungarian neurosurgeon who came to the U.S. and shifted his focus to the field of neuroradiology. He was the B. Leonard Holman Professor of Radiology at Harvard Medical School and the vice chair of radiology at Brigham and Women's Hospital (BWH) in Boston. Jolesz and his colleagues at GE Healthcare co-invented the very first interventional MR device, known as the GE 0.5T Signa SP (Fig. 2), which was placed in an operating room at BWH in 1994. The addition of the MR device to the hospital system allowed surgeons and radiologists to perform MRI-guided surgeries and procedures with real-time MR feedback at all points during intervention.

Prior to collaborating on the development of iMRI, Lewin served as the director of the Division of Magnetic Resonance Imaging at the University Hospitals of Cleveland, and as vice chair for research and academic affairs in the Department of Radiology at Case Western Reserve University. He later became the chair of radiology at Johns Hopkins in Baltimore. Similarly, Kahn was working in the Department of Diagnostic and Interventional Radiology at Leipzig University Hospital in Germany during this timeframe.

Building on the foundational work of these pioneers and the growing need for a collaborative, interdisciplinary forum, the field naturally progressed toward creating a

recurring venue for knowledge exchange, technical advancement, and clinical collaboration. This led to the establishment of the iMRI Symposium, which has since become a cornerstone event for the global iMRI community.

The iMRI Symposium provides an ideal platform for researchers, clinicians, and healthcare professionals to present their latest results and interact with key opinion leaders and innovators in the field. Sessions span both technical and clinical domains, featuring lectures by invited speakers, as well as scientific papers.

The event is now jointly organized by the Department of Radiology at Brigham and Women's Hospital, Harvard Medical School in Boston; the Department of Radiology and Radiological Science at Johns Hopkins University in Baltimore; and the Department of Diagnostic and Interventional Radiology at Leipzig University Hospital, in close cooperation with Hannover Medical School, the University of Magdeburg, and Emory Healthcare in Atlanta. The meeting is typically endorsed by the International Society for Magnetic Resonance in Medicine (ISMRM), and by the European Society for Magnetic Resonance in Medicine and Biology (ESMRMB). It is supported by the Ferenc Jolesz National Center for Advanced Technologies for Image Guided Therapy (NCIGT) at Harvard Medical School. The upcoming 15th meeting is scheduled to be held in Boston in 2026.

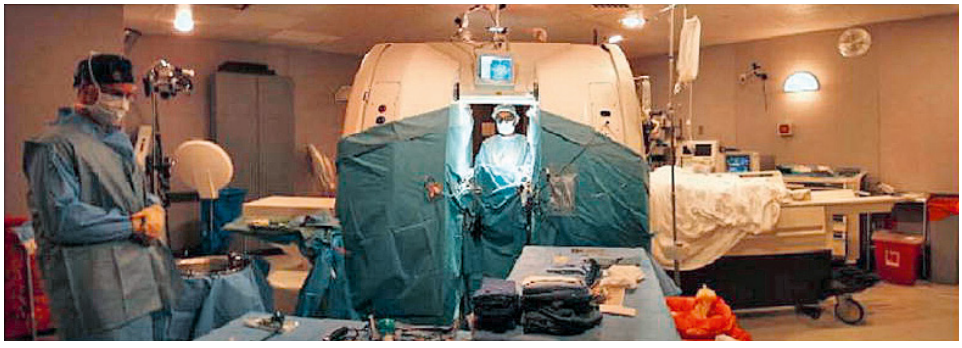
The 14th iMRI Symposium, held October 17–18, 2024, in Annapolis, MD, USA (Fig. 3), showcased a diverse range of research reflecting the rapid evolution of MRI-guided therapy. Key focus areas included the growing clinical potential of low-field MRI in interventional workflows, the expansion of MRI into new procedural applications and disease indications, the integration of devices and AI for real-time image guidance, and early efforts to bring iMRI out of tertiary care centers and into the community through mobile platforms [1]. Collectively, these developments point to a shared vision across the iMRI community: making MRI-guided interventions safer, more accessible, and more adaptable to routine clinical practice.

Low-field MRI in interventional workflows

Among the topics highlighted at the symposium, one of the most exciting directions in iMRI today is the increasing adoption of low-field systems, particularly those operating at 0.55T. These platforms offer several advantages that are especially relevant for expanding access to iMRI: lower system and maintenance costs, reduced installation requirements, fewer susceptibility artifacts, and a larger bore that enhances procedural access and patient comfort while improving compatibility with implants and interventional devices [2]. Together, these features are making iMRI more compatible and better suited for diverse clinical environments, including those outside of major academic centers.

Recent studies have shown that low-field MRI is feasible and that it functionally enables a wide range of technically demanding procedures. In a prospective study by Kaur et al., a 0.55T scanner was successfully used for in-bore prostate biopsies performed via both transrectal and transgluteal approaches. Despite the lower field strength, lesion identification remained robust, even in challenging cases such as in patients with hip prostheses. Importantly, the procedure times and diagnostic yield were comparable to higher-field systems, with some additional advantages such as reduced artifacts near implants [3].

Another notable advancement comes from selective renal artery embolization performed in a preclinical model under real-time 0.55T MRI guidance. Ooms et al. used prototype MR-visible catheters to achieve accurate navigation, successful coil deployment, and clear visualization of perfusion changes without radiation or iodinated contrast. Real-time balanced steady-state free precession (bSSFP) imaging was used for device navigation, while T1-weighted fast low-angle shot (FLASH) sequences enabled dynamic assessment of perfusion before and after embolization [4]. This is a compelling example of how low-field MRI can enable complex catheter-based vascular interventions with real-time MRI guidance, demonstrating the feasibility of fully MRI-based vascular navigation and therapy.



2 The GE 0.5T Signa SP. *Reprinted with permission from Mislow JM, Golby AJ, Black PM. Origins of intraoperative MRI. Neurosurg Clin N Am. 2009;20(2):137–46.*

A third study explored the use of 0.55T MRI for musculoskeletal soft tissue biopsies, targeting lesions that were difficult to visualize with ultrasound or CT, or were located near critical structures. Malhotra et al. utilized the system's wide bore to establish a posterior biopsy window with flexible coil placement, enabling successful targeting of parasacral, periprosthetic, and deep thigh masses. Despite early technical challenges with coil setup and sequence optimization, they achieved consistent visualization using a T2 HASTE sequence and performed successful biopsies using standard MR-compatible devices. All procedures yielded diagnostic samples, with an average procedure time of 57 minutes, comparable to CT-guided workflows [5].

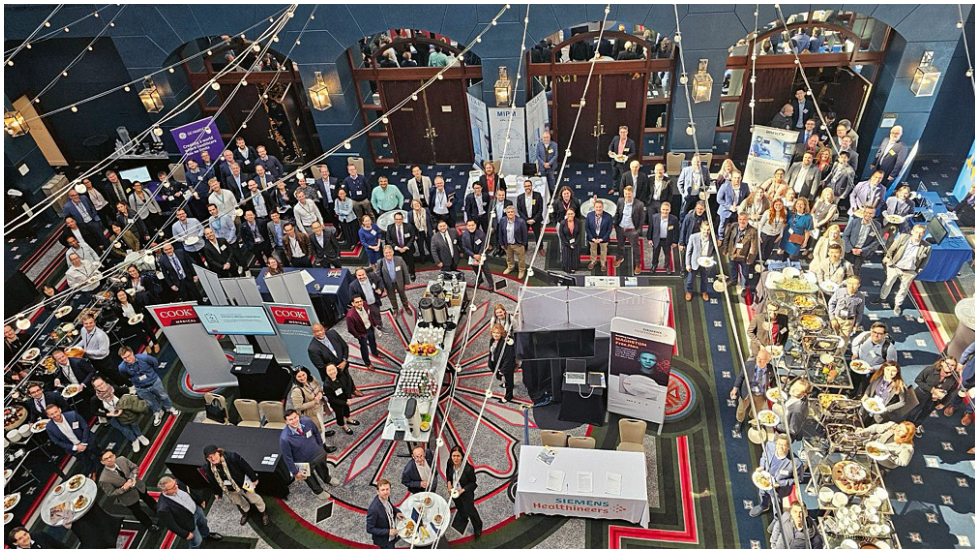
Collectively, these studies illustrate a shift in the iMRI landscape. Low-field MRI, once considered a technical compromise, is now emerging as a viable and versatile platform for real-time, image-guided interventions due to improvements in image quality and temporal resolution. As imaging protocols evolve and MR-compatible devices become more widely available, 0.55T systems are increasingly capable of supporting complex procedures with both precision and efficiency. By lowering technical and logistical barriers, low-field MRI has the potential to make iMRI more accessible, scalable, and cost-effective, particularly in centers without access to high-field infrastructure. These innovations not only demonstrate technical feasibility, but also reflect the broader movement to extend iMRI into new therapeutic indications.

Expanding clinical indications and procedure types

Abstracts in this section demonstrate how MRI guidance is being applied across new clinical domains, irrespective of field strength. A particularly exciting direction is the use of iMRI beyond its traditional applications, namely, oncology and neurosurgery. Recent work has demonstrated that iMRI has potential in a broader array of interventions, including brachytherapy, neuromodulation, vascular stenting, and non-thermal ultrasound-based therapies. This signals a meaningful expansion of iMRI into emerging areas of clinical practice.

Haghpanah et al. explored the use of MRI-guided catheter-based brachytherapy for the treatment of primary and secondary liver tumors, demonstrating how MRI can facilitate not only diagnosis or ablation, but also precise, image-guided radiation therapy. In this prospective single-center trial, 27 patients with 54 liver lesions were treated using an MRI-guided approach for catheter placement, followed by high-dose-rate (HDR) brachytherapy. Real-time gradient-echo sequences enabled accurate navigation under conscious sedation, while 3D T1-weighted imaging supported detailed treatment planning. The mean dose per lesion was 18.9 Gy, and only 7.4% of patients experienced minor, self-limited bleeding. With its combination of precision, low complication rates, and effective dosing, this technique has potential as a minimally invasive, radiation-free treatment option, particularly for small liver lesions [6].

Exploring a novel therapeutic direction, Kamireddy et al. demonstrated the feasibility of MRI-guided vagal cryoablation for the treatment of obesity in a chronic canine model. Using a 1.5T MRI system and an MR-compatible cryoprobe, the procedure enabled accurate targeting of the posterior vagal trunk, an anatomically challenging location, without causing injury to adjacent critical structures. The study highlights how real-time MRI guidance can facilitate safe and precise probe placement in complex regions, positioning iMRI as a promising platform for image-guided neuromodulation in evolving areas of clinical need such as metabolic disorders [7].



3 The 14th iMRI Symposium, October 2024, Annapolis MD, USA. Group photo in the industry exhibition hall.

In a novel preclinical study using a 3T MRI system, Regler et al. also demonstrated the feasibility of MRI-guided venous stenting with a newly developed MR-compatible braided nitinol stent and delivery system. Traditional venous stents are often incompatible with MRI due to significant artifacts and poor visibility. However, this platform was specifically designed to address those limitations, enabling precise navigation, real-time deployment, and repeated repositioning without compromising accuracy. Tested in a realistic iliac vein phantom, the system achieved successful stent placement in all cases, with a 95% apposition rate to the vessel wall and minimal imaging artifacts, setting the stage for future in vivo applications of MRI-guided venous interventions [8].

Lastly, Ishak et al. introduced a method called MR cavitation imaging as a non-invasive technique to visualize and quantify microbubble activity during non-thermal focused ultrasound (FUS) therapies. These therapies, such as sonoporation, rely on ultrasound-induced cavitation to temporarily permeabilize physiological barriers. In this study, MR images were acquired using a rapid HASTE sequence synchronized with ultrasound pulses of varying duration and intensity, allowing researchers to capture real-time cavitation effects. The technique generated cavitation maps based on localized MR signal drops, with a defined cavitation index that increased with both acoustic pressure and pulse duration. When compared with passive cavitation detector data, which is the gold standard for monitoring microbubble activity, MR-based cavitation maps showed strong agreement, particularly in identifying inertial cavitation [9]. Although not an interventional therapy itself, MR cavitation imaging represents a powerful tool for monitoring and optimizing microbubble-based treatments, with early swine experiments showing promising translational potential.

Together, these studies demonstrate that iMRI is actively being reimagined for new clinical indications, from vascular therapies and targeted radiotherapy to ultrasound-driven drug delivery. This growing versatility broadens the reach of iMRI and positions it as a key modality in the next generation of minimally invasive treatment platforms.

Devices and AI for instrument tracking and real-time guidance

Another critical area of innovation is the integration of smart hardware and AI to improve real-time image guidance. These efforts are aimed at enhancing visibility, reducing operator dependence, and streamlining workflows – especially in settings where traditional imaging may be limited by resolution, speed, or user expertise.

A notable contribution in this area came from Su et al., who tested deep learning reconstruction for real-time imaging during abdominal needle procedures on a 0.55T MRI scanner. Using a biopsy phantom and a healthy volunteer, the researchers compared deep learning to two standard reconstruction techniques, GRAPPA and compressed sensing, and found that deep learning consistently produced sharper images with fewer artifacts and less noise. These improvements helped make key anatomical structures such as the liver more clearly visible, even with fast imaging. By improving both image quality and speed, deep learning reconstruction helped overcome the usual limitations of low-field MRI and showed strong potential to enhance real-time guidance during interventional procedures [10].

With the aim of improving visualization during transperineal prostate procedures, Kowal et al. developed an MR-active needle guide that includes a wireless metasurface coil (an advanced device designed to boost signal strength) along the needle path. When tested in a phantom on a 3T MRI system, the coil improved the signal-to-noise ratio (SNR) by up to 16 times at the needle entry point, with noticeable enhancement up to 6 cm deep. This means that the entire path from skin to target became more visible on MRI, helping radiologists place needles more accurately and reducing procedure time. The study shows how smart coil design can improve MRI-guided interventions by making key structures easier to see throughout the procedure [11].

Kehrein et al. demonstrated a novel approach to temperature monitoring during prostate tumor ablation using MR fingerprinting (MRF), an advanced imaging method that allows multiple tissue properties to be measured simultaneously. In this study, MRF was used to quantify temperature changes by analyzing T1 relaxation times, which vary with heat. Researchers scanned a phantom containing tissue-mimicking materials and used 35 different image acquisitions with varying flip angles and timings to create detailed "fingerprints" of the tissue response. A convolutional neural network was then trained to convert these fingerprints into temperature maps. Impressively, the AI model reduced the image reconstruction time from over an hour to just 50 seconds, making it fast enough for potential use during real procedures. These results suggest that MRF, combined with deep learning, could enable accurate, real-time temperature mapping to help guide and adjust ablation therapy directly during treatment [12].

Together, these innovations aim to simplify procedures while enhancing their precision. By combining low-field systems with AI-based imaging, adaptive coils, and user-friendly tools, researchers are closing the gap between cutting-edge image guidance and everyday clinical implementation.

Bringing iMRI to the community: The mobile MRI experience

Historically, iMRI has been limited to tertiary centers due to the need for complex infrastructure and demanding technical support. A recent feasibility study by Chopra et al. presented at the 14th iMRI Symposium demonstrated that MRI-guided transurethral ultrasound ablation for localized prostate cancer can be safely and effectively delivered using a mobile MRI trailer equipped with a 1.5T MAGNETOM Aera system (Siemens Healthineers, Erlangen, Germany).

To account for challenges unique to the mobile setting, such as vibration, radiofrequency noise, and environmental magnetic interference, the team performed extensive testing using gel phantoms, simulating real-world conditions like nearby vehicle movement and door activity. By maintaining an 8-foot buffer zone around the scanner, they successfully limited proton resonance frequency shift (PRFS) thermometry artifacts to under 1°C, ensuring accurate thermal mapping.

In a pilot series of six patients, the workflow was adapted using small-footprint MRI-compatible ventilators and monitors, with stretcher access carefully coordinated to fit the mobile space. Mean procedure times mirrored those in standard hospital-based settings, and all patients recovered in the adjacent facility's post-anesthesia care unit [13].

This study confirms that high-precision, MRI-guided therapy can be delivered outside traditional settings without compromising safety or effectiveness. Beyond transurethral ultrasound ablation, the mobile MRI framework could support a wider range of image-guided interventions, bringing advanced iMRI capabilities to clinics and communities outside of the tertiary care setting.

Advances in MR thermometry for thermal ablation monitoring

Magnetic resonance (MR) thermometry is revolutionizing the monitoring of thermal ablation techniques, such as microwave ablation (MWA), cryoablation, and high-intensity focused ultrasound (HIFU) by providing real-time temperature mapping. Recent studies highlight innovative approaches to enhance MR thermometry across different ablation modalities, particularly in low-field MRI and challenging temperature ranges.

In a study conducted at Hannover Medical School, Belker et al. evaluated MRI-guided MWA on a bioprotein phantom using a 0.55T MRI scanner. Employing PRFS thermometry, they monitored the cooling process after ablation with a temperature uncertainty of 0.44 ± 0.03°C. The ablation zone, assessed via T1 and T2 mapping, showed consistent diameters of approximately 2.5–2.6 cm at both 0.55T and 1.5T, aligning with visible coagulation zones. This demonstrates the feasibility of low-field MR thermometry for MWA, despite challenges like reduced signal-to-noise ratio, paving the way for cost-effective and safer ablation monitoring [14].

Gutt et al. addressed the complexities of MR thermometry during cryoablation, where frozen tissue typically appears as a signal void. Using an ultrashort echo-time (UTE) sequence with a FLORET (Fermat looped, orthogonally encoded trajectories) readout on a 1.5T scanner, researchers measured temperature changes in ex vivo bovine liver cooled with dry ice. The FLORET sequence achieved a temporal resolution of 6.12 seconds and a spatial resolution of 2.5 mm. By fitting a monoexponential model to signal intensity, they achieved a mean temperature deviation of 3.2 ± 1.7°C, enabling temperature mapping at the subzero levels critical for tissue necrosis (-20 to -40°C) [15].

For MRI-guided HIFU of the prostate, Schroer et al. developed a denoising technique using KalmanNet with proper orthogonal decomposition (POD) to filter 3D PRFS thermometry data in real time. Applied to data from eight patients on a 1.5T scanner, this method reduced mean squared errors from 20.04 dB to 15.39–15.94 dB, with inference times as low as 0.019 seconds per temperature map. This approach enhances the accuracy and speed of temperature monitoring, which is crucial for precise ablation control [16].

These advancements underscore the potential of tailored MR thermometry techniques to improve the safety and efficacy of thermal ablation across diverse clinical scenarios.

Conclusion

The iMRI Symposium highlighted exciting breakthroughs in iMRI, which marked a shift towards greater accessibility and broader clinical impact. Low-field MRI, especially at 0.55T, has moved beyond being merely a cost-saving diagnostic alternative to 1.5T and 3T systems, and is proving itself to be effective for complex interventions typically reserved either for high-field systems or, more commonly, for X-ray or CT guidance. Moreover, MRI-guided procedures are being used increasingly in areas such as vascular interventions, neuromodulation, and targeted radiation therapies, reflecting the field's expanding clinical reach. Innovations in MR-compatible devices and AI-driven imaging techniques are enhancing real-time image quality, simplifying procedures, and making advanced treatments more feasible in everyday practice. Additionally, the introduction of mobile MRI platforms demonstrates that sophisticated image-guided therapies can be safely delivered beyond major academic centers in community settings. These developments collectively emphasize that iMRI is a critical player in the future of minimally

invasive treatments, promising wider availability, improved precision, and ultimately better patient care across many healthcare environments.

References

1 Book of Abstracts. 14th Interventional MRI Symposium, Oct 17–18, 2024, Annapolis, MD, USA. 2024. Available from: https://hopkinscme.cloud-cme.com/assets/HopkinsCME/data/iMRI%20Brochure%20with%20Abstract%20Titles%20and%20Poster%20Listing.pdf
2 Shetty AS, Ludwig DR, Ippolito JE, Andrews TJ, Narra VR, Fraum TJ. Low-Field-Strength Body MRI: Challenges and Opportunities at 0.55 T. Radiographics. 2023;43(12):e230073.
3 Kaur T, Jiang Y, Seiberlich N, Hussain H, Wells S, Wie J, et al. Feasibility of MRI-guided In-Bore Prostate Biopsies at 0.55T [Abstract]. In: Book of Abstracts. 14th Interventional MRI Symposium, Oct 17–18, 2024, Annapolis, MD, USA. 2024:30.
4 Ooms N, Brandner E, Roll J, Anderson R, Krieger J, Sutphin P, et al. Selective Segmental Renal Artery Embolization Under 0.55T: Real-Time Navigation, Visualization, and Confirmation in a Porcine Model [Abstract]. In: Book of Abstracts. 14th Interventional MRI Symposium, Oct 17–18, 2024, Annapolis, MD, USA. 2024:58.
5 Malhotra G, Buckwalter K, Morehouse J. Musculoskeletal Soft Tissue Biopsies at 0.55T [Abstract]. In: Book of Abstracts. 14th Interventional MRI Symposium, Oct 17–18, 2024, Annapolis, MD, USA. 2024:143.

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6 Haghpanah A, Fabritius MP, Dietrich O, Puhr-Westerheide D, Schmidt VF, Corradini S, et al. MR guided catheter-based radiotherapy/brachytherapy of liver tumours – first experience and feasibility [Abstract]. In: Book of Abstracts. 14th Interventional MRI Symposium, Oct 17–18, 2024, Annapolis, MD, USA. 2024:63.
7 Kamireddy A, Weiss CR, Rice C, Ivkov E, Shin EJ, Anders RA, et al. MR-Guided Vagal Cryoablation for the Treatment of Obesity in a Canine Model - Preliminary Results [Abstract]. In: Book of Abstracts. 14th Interventional MRI Symposium, Oct 17–18, 2024, Annapolis, MD, USA. 2024:16.
8 Regler L, Reiss S, Verloh N, Düring K, Uller W, Bock M. In-vitro MR-guided Venous Stenting with a Novel MR-compatible Delivery System. [Abstract]. In: Book of Abstracts. 14th Interventional MRI Symposium, Oct 17–18, 2024, Annapolis, MD, USA. 2024:56.
9 Ishak O, Breton E, Cabras P, Dumont E, Josset A, Larrat B, et al. MR Cavitation Imaging: a new method for monitoring non-thermal ultrasound therapies [Abstract]. In: Book of Abstracts. 14th Interventional MRI Symposium, Oct 17–18, 2024, Annapolis, MD, USA. 2024:7.
10 Su P, Maier F, Cui S, Nickel MD, Bhat H, Pang J. Improved MRI Guided Interventions at 0.55T: Real-time Interactive Imaging with Deep Learning Reconstruction [Abstract]. In: Book of Abstracts. 14th Interventional MRI Symposium, Oct 17–18, 2024, Annapolis, MD, USA. 2024:12.
11 Kowal R, Knull L, Hubmann MJ, Vogt I, Düx D, Gutberlet M, et al. MR-Active Needle Guides with Wireless Metasurface Coils for Transperineal Prostate Interventions [Abstract]. In: Book of Abstracts. 14th Interventional MRI Symposium, Oct 17–18, 2024, Annapolis, MD, USA. 2024:28.
12 Kehrein F, Schad LR, Zöllner FG. Interventional MR Thermometry for Prostate Tumor Ablation via Quantitative T1 Mapping Using MR Fingerprinting and Deep Learning [Abstract]. In: Book of Abstracts. 14th Interventional MRI Symposium, Oct 17–18, 2024, Annapolis, MD, USA. 2024:108.
13 Chopra R, Leung B, Childs A, Staruch R, Cookson M, Stratton K. Moving iMRI from the hospital to the community: First experience and technical feasibility of delivering MRI-controlled prostate ablation in a mobile MRI [Abstract]. In: Book of Abstracts. 14th Interventional MRI Symposium, Oct 17–18, 2024, Annapolis, MD, USA. 2024:31.
14 Belker O, Gerlach T, Krafft AJ, Maier F, Requardt M, Horstmann D, et al. First experience with MR thermometry and assessment of the ablation zone in microwave ablation of a bioprotein phantom on a 0.55T scanner [Abstract]. In: Book of Abstracts. 14th Interventional MRI Symposium, Oct 17–18, 2024, Annapolis, MD, USA. 2024:17.
15 Gutt M, Belker O, Scheller J, Wacker F, Gutberlet M, Hensen B. MR-Thermometry at Subzero Temperatures with a FLORET Readout in Ex-vivo Bovine Liver [Abstract]. In: Book of Abstracts. 14th Interventional MRI Symposium, Oct 17–18, 2024, Annapolis, MD, USA. 2024:19.
16 Schrör S, Peters I, Hellms S, Horstmann D, Belker O, Gutt M, et al. KalmanNet using POD: Real-time Denoising of 3D MR Thermometry during MR-guided Prostate HIFU [Abstract]. In: Book of Abstracts. 14th Interventional MRI Symposium, Oct 17–18, 2024, Annapolis, MD, USA. 2024:34.

The Spectrum of Interventional MRI

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Abstract

Clinical use of magnetic resonance imaging (MRI) for image-guided procedures began in the late 1980s. However, early procedures were limited by tools, in-bore access to the patient, and MR imaging limitations. Interventional MRI (iMRI) offers some natural advantages including superior soft tissue resolution, ease of multiplanar imaging, lack of ionizing radiation, and the ability to re-image the same slice. MRI guidance is particularly advantageous when the pathology can be best or only visualized with MRI. There has been tremendous growth in clinical applications and positive patient outcomes of iMRI over the past three decades, and the community has benefited from close collaboration between interventional radiologists, MR physicists, and MR nurses. There has been tremendous growth in clinical applications of iMRI over the last 35+ years [1]. The purpose of this article is to give a high-level overview of the breadth of interventional MRI.

Introduction

Shortly after the introduction of clinical diagnostic magnetic resonance imaging (MRI) in the 1980s, diagnostic and interventional radiologists recognized the superior soft tissue contrast of MRI and began to explore the use of MRI guidance during interventional procedures, particularly for head and neck lesions [2–4]. However, early applications of interventional MRI (iMRI) were limited due to the lack of dedicated iMRI magnets, pulse sequences, procedural suites, and equipment. Over the next three decades, significant advancements in iMRI-conditional technology coupled with developments in dedicated iMRI procedural suites enabled significant growth and development of clinical body iMRI applications including aspiration, localization, biopsy, and ablation [5, 6]. MRI offers significant advantages including: superior soft tissue contrast and anatomic detail, leading to increased lesion conspicuity; ease of multiplanar imaging; multiparametric imaging capabilities; lack of ionizing radiation; the ability to monitor effects of treatment in near real time; and the ability to re-image the same slice [7, 8].

With the growth of dedicated clinical iMRI services, safety considerations in the iMRI environment have become paramount [9, 10]. Moreover, systematic physics and clinical safety testing have led to the safe use of previously MR-conditional and unsafe devices in the MR environment, further enabling expansion of clinical body iMRI applications [9, 11–13]. Likewise, with the growth of dedicated iMRI magnets, various MR pulse sequences have been optimized with tradeoffs between image acquisition speed, signal-to-noise ratio (SNR), and spatial and contrast resolution [14, 15].

Additionally in this time period, there has been tremendous development of commercially available MR-conditional needles, and biopsy and ablation devices, which has further enabled the growth of body iMRI applications [10, 16]. Currently, there are a variety of devices approved by the Food and Drug Administration (FDA) for performing MRI-guided and monitored cryoablation, laser ablation, microwave ablation (MWA), radiofrequency ablation (RFA), and focused ultrasound (MRgFUS). Current iMRI applications include localization, biopsy, and sclerotherapy of lesions with poor soft tissue contrast on other imaging modalities, and thermal ablation for benign and malignant neoplastic processes.

Clinical applications of body interventional MRI

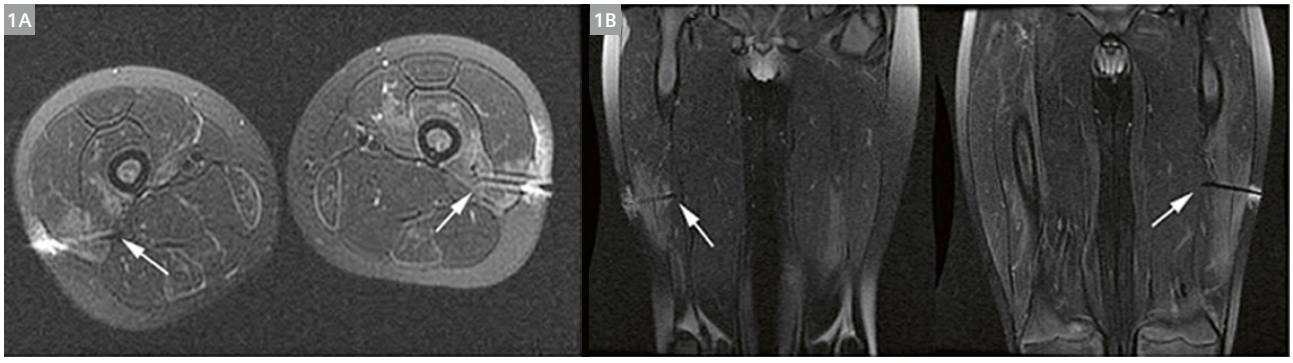
There has been tremendous growth in applications of body iMRI, including localization, drainage, biopsy, and sclerotherapy of lesions poorly visualized with ultrasound (US) or computed tomography (CT) [7, 8, 16–18]. This review focuses on many, but not all, iMRI applications as these continue to grow.

Localization

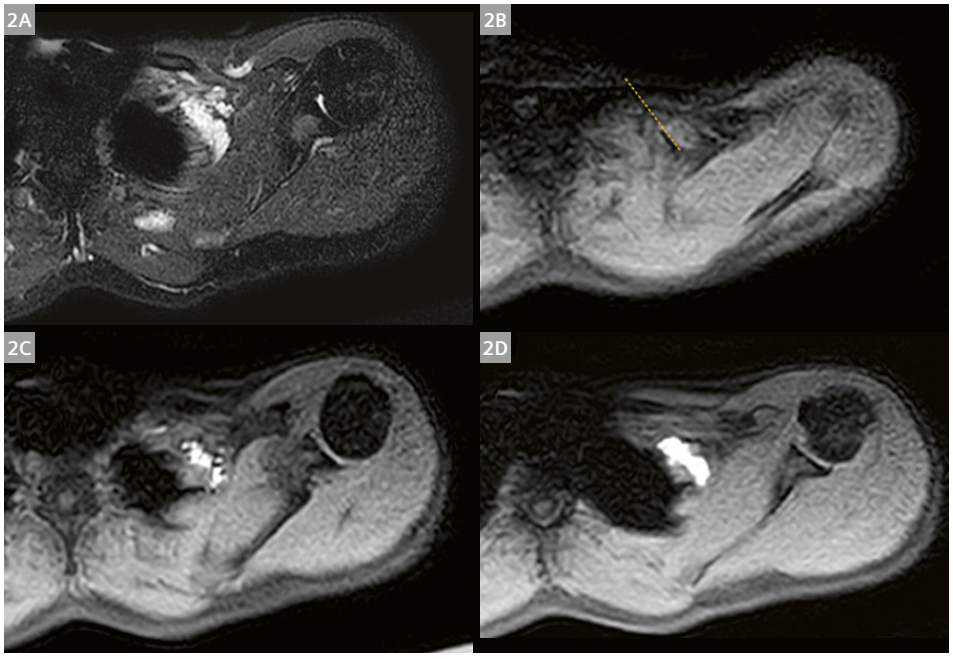
Soft tissue pathology with poor soft tissue contrast on US or CT may be particularly amenable to MRI-guided wire localization when precise localization of a pathology with a patchy or heterogenous distribution is needed prior to targeted surgical biopsy. Examples include intramuscular lymphoma and juvenile dermatomyositis (Fig. 1) [19, 20].

Sclerotherapy

Traditionally, percutaneous sclerotherapy of venous malformations has been performed with a combination of US and fluoroscopic guidance. However, when venous malformations are poorly conspicuous on US, MRI guidance for needle placement prior to sclerotherapy may be utilized, particularly given the inherent high T2-weighted signal within most venous malformations (Fig. 2). Prior studies have shown that MRI-guided percutaneous sclerotherapy is safe, technically feasible, and effective in the treatment of peripheral soft tissue venous malformations at both 1.5T and 3T [21, 22].



1 MRI of the needle position within the high T2 signal in the vastus lateralis. **(1A)** Axial and **(1B)** coronal with the localizing wire in place and subsequent surgical biopsy confirming juvenile dermatomyositis [40].



2 **(2A)** T2 with fat saturation demonstrates a bright slow-flow vascular malformation. **(2B)** shows a 22Ga ITP needle placed into the vascular malformation. **(2C)** demonstrates injection of dilute 1:10 gadolinium into the vascular malformation confirming the intra-luminal position. **(2D)** demonstrates injection of a gadolinium and bleomycin mixture into the lesion to perform sclerotherapy. (Unpublished images)

Biopsy

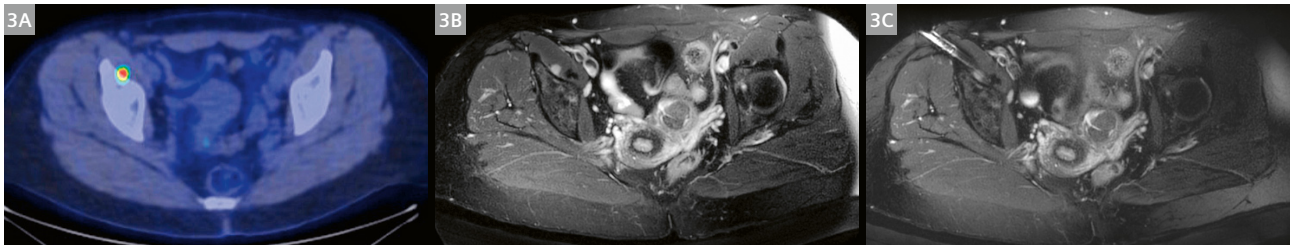
Similar to lesion localization, soft tissue masses with poor soft tissue contrast on US or CT may be suitable for MRI-guided biopsy. This may be performed using freehand, US-assisted or guidance-grid techniques depending on lesion location and organ movement [8, 16, 18, 23]. Prostate and seminal vesicle biopsy via a transperineal approach with a guidance grid is well suited for MRI-guided biopsy [23–25]. Small liver or soft tissue lesions (Fig. 3) seen on diagnostic MRI and positron emission tomography (PET) that cannot be localized by grayscale, color doppler, or contrast-enhanced US, US fusion, or CT are excellent candidates for MRI-guided freehand biopsy. For patients with prior non-diagnostic biopsies of small or technically difficult lesions, consideration can be given to having an on-site cytopathologist for immediate review of the diagnostic adequacy of the biopsy specimen.

Ablation

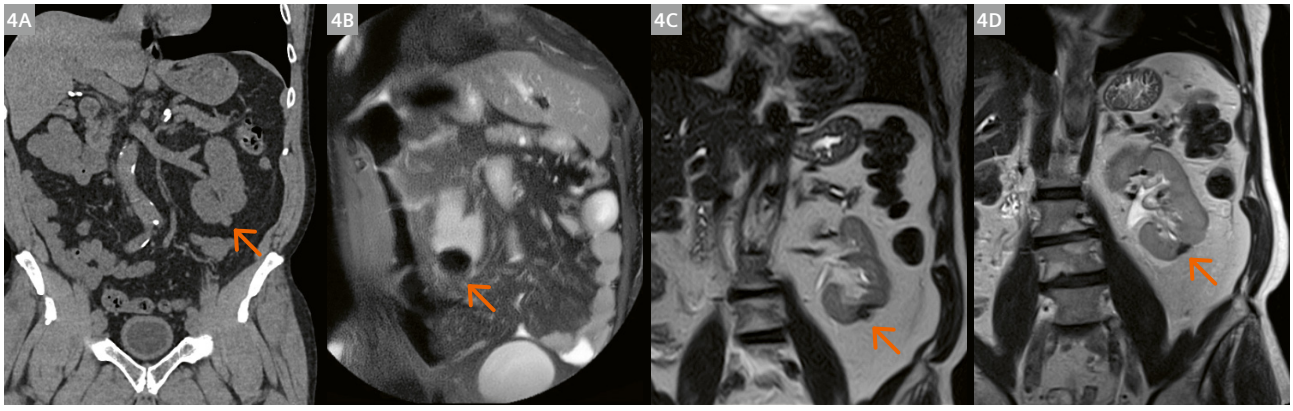
Image-guided percutaneous thermal ablation with MRI is enhanced with more precise lesion visualization and the ability to monitor ablation temperature: either heat or cold. While US, and to a lesser extent CT, can provide some real-time ablation monitoring, MRI has superior soft tissue contrast and, together with MR thermometry, offers a unique feature for monitoring the ablation procedure.

Kidney

Ablation of renal neoplasms is most commonly performed under US and/or CT guidance using cryoablation, RFA or MWA [26, 27]. However, MRI-guided cryoablation has been shown to be safe and effective for treatment of small renal neoplasms [28]. In our practice, MRI-guided cryoablation is reserved for ablation of renal neoplasms that are intra-parenchymal or endophytic and poorly visualized on US or non-contrast CT (Fig. 4).



3 MRI-guided muscle lesion biopsy to determine benign versus malignant. **(3A)** shows an axial fluorodeoxyglucose (FDG) PET-CT image demonstrating a lesion with increased activity in the right iliopsoas muscle. CT-guided biopsy was unsuccessful. **(3B)** demonstrates a T2-weighted MR lesion in the same location as the abnormal PET activity. **(3C)** demonstrates an 18Ga ITP biopsy needle through the lesion. (Unpublished images)



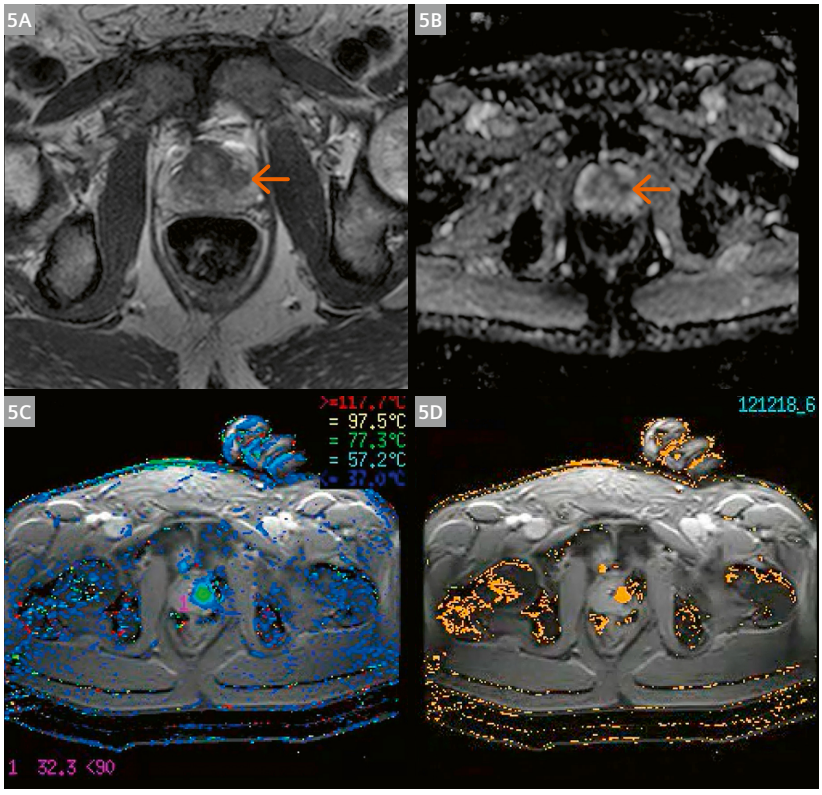
4 MRI-guided renal mass ablation for a 65-year-old man with a history of right kidney resection for renal cell carcinoma and development of a new left lower pole renal mass. **(4A)** shows a non-contrast CT image demonstrating a tiny mass on the lower pole of the left kidney. **(4B)** demonstrates T2-weighted MR images showing the iceball encompassing the tiny nodule. **(4C)** shows T2-weighted images three months post-ablation. **(4D)** shows T2-weighted images two years post-ablation. (Unpublished images)

Prostate and seminal vesicles

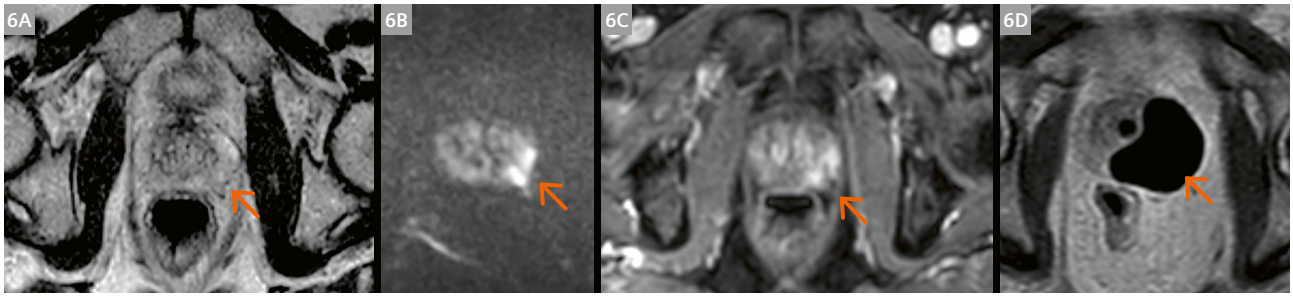
MRI-guided laser ablation of the prostate with MR thermometry in a 64-year-old man with rising prostate specific antigen (PSA) and biopsy-positive Gleason 7 (4+3) disease in the left mid prostate: MRI-guided thermometry allows continuous monitoring of the ablation heating during treatment (Fig. 5).

MRI-guided focal cryoablation of the prostate for Gleason 7 (3+4) disease in the left anterior prostate: Ice ball monitoring is achieved with a balanced HASTE updating every 10–20 seconds (Fig. 6).

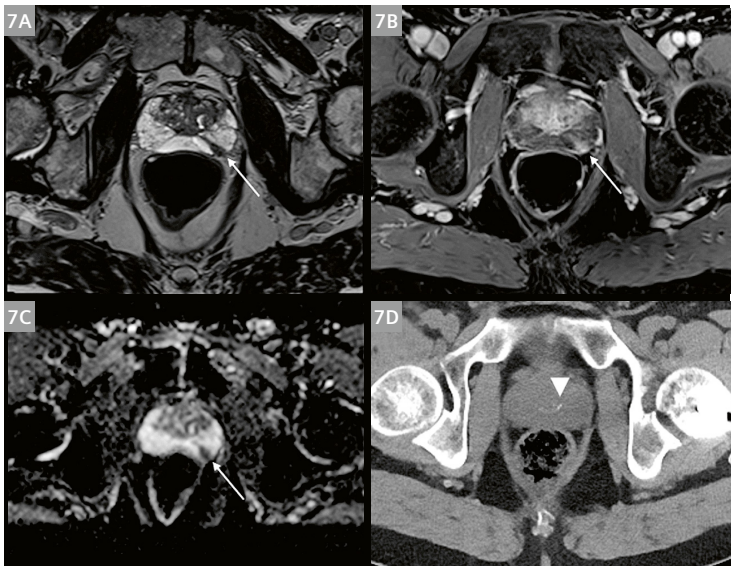
MRI-guided focused transurethral ultrasound ablation (TULSA) of the prostate for Gleason 7 disease in the left posterior prostate: The TULSA treatment device (TULSA-PRO, Profound Medical Corp., Mississauga, Canada) was placed over the wire into the urethra and positioned with the transducers in the prostatic tissue. During treatment, the MR temperature mapping is used to guide and control the treatment frequency and the power, which is monitored continuously.



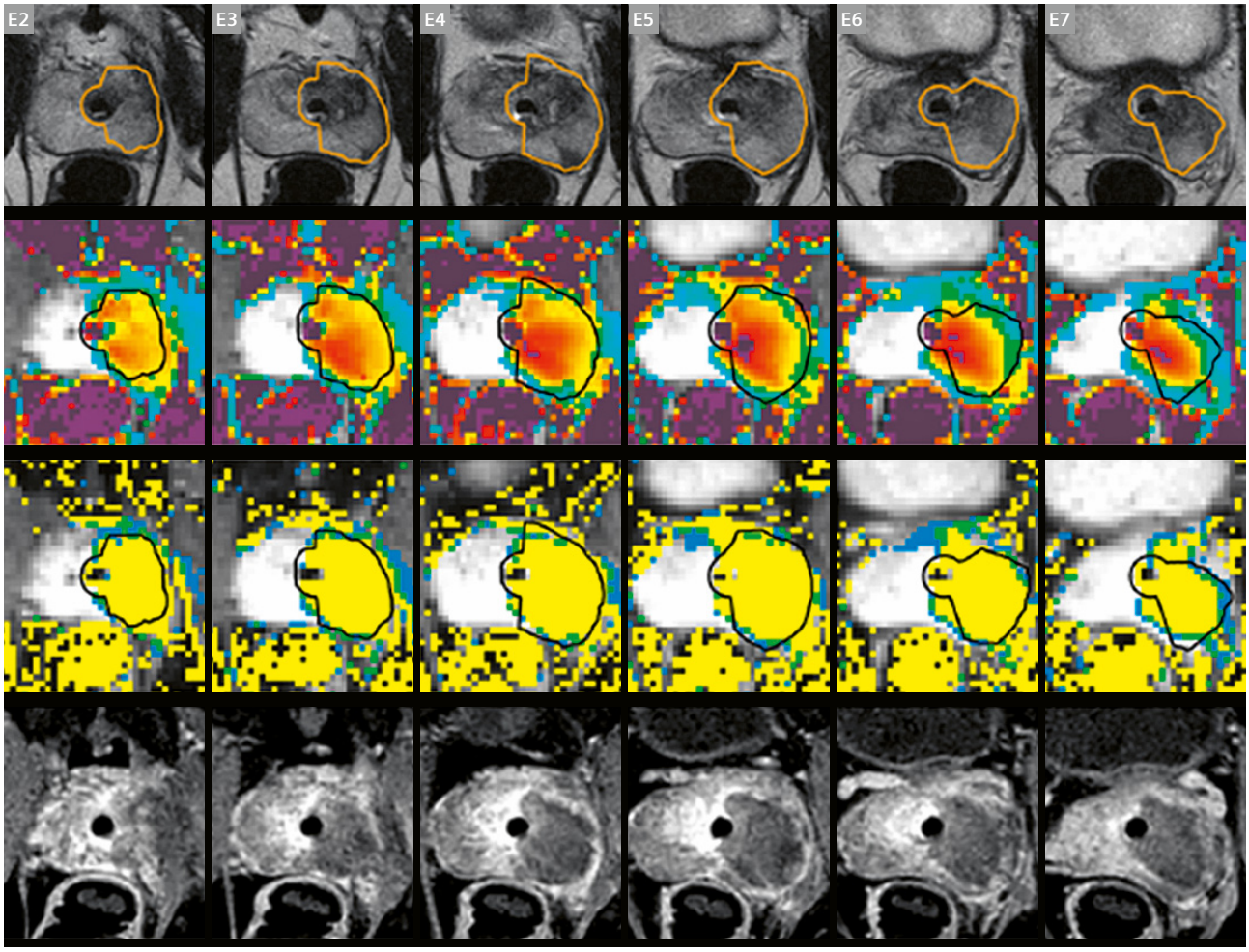
5 **(5A)** demonstrates T2-weighted imaging of the prostate showing a lesion in the left prostate. **(5B)** shows the ADC map demonstrating the restricted diffusion in the left prostate lesion. **(5C)** is the phase image during MR thermometry demonstrating heating in the left prostate. **(5D)** is the calculated damage map using time and temperature inputs into an Arrhenius equation. (Unpublished images)



6 **(6A)** shows a T2-weighted image demonstrating decreased signal in the left posterior prostate (orange arrow). **(6B)** demonstrates restricted diffusion in this same area (orange arrow). **(6C)** demonstrates Gadolinium enhancement in this same area (orange arrow). **(6D)** demonstrates maximal ice ball formation encompassing the lesion (orange arrow). (Unpublished images)



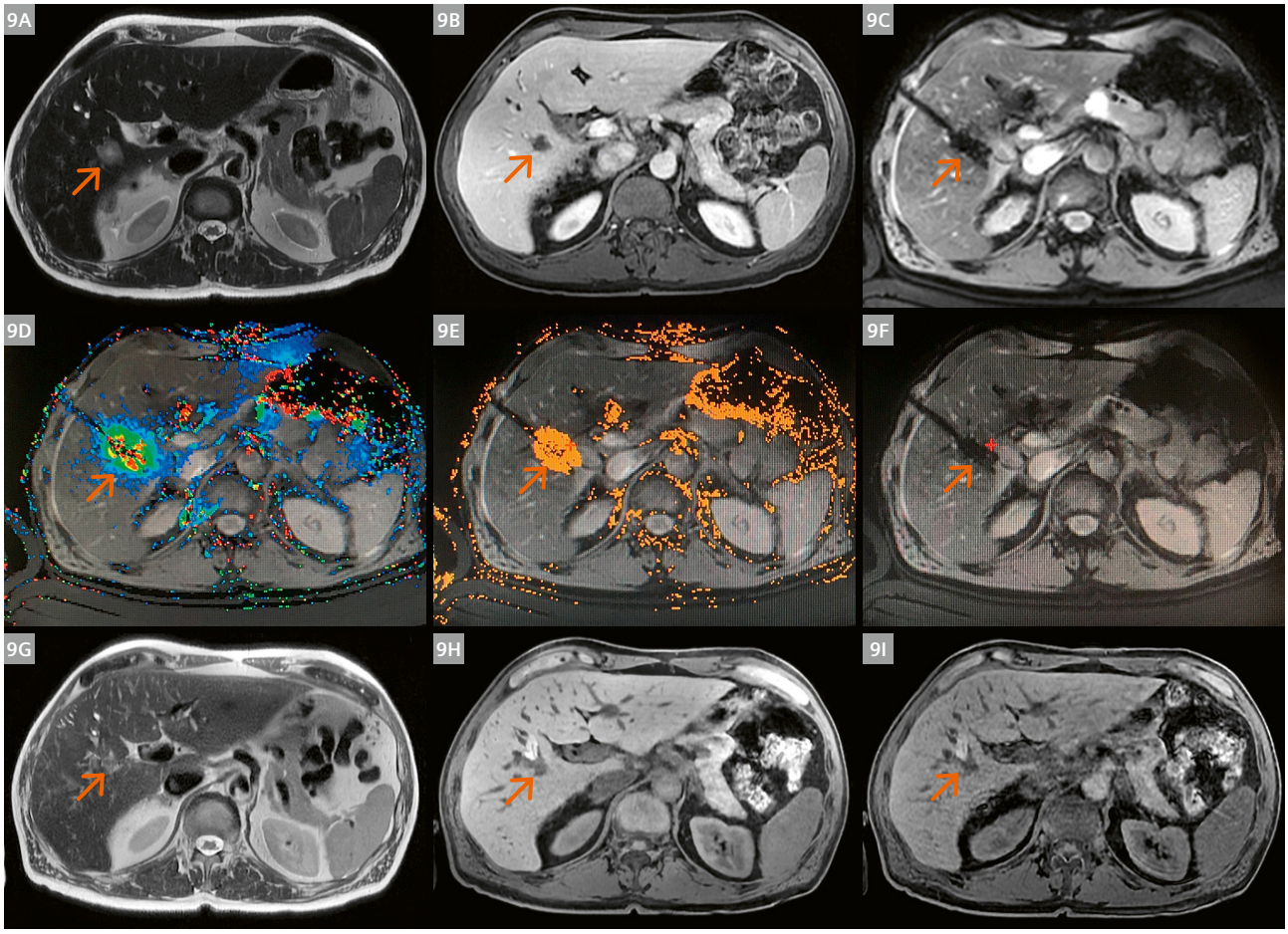
7 Pre-treatment workup for the MRI-guided TULSA for prostate cancer. **(7A)** demonstrates T2 abnormality in the left posterior peripheral zone of the prostate (white arrow). **(7B)** demonstrates hyperenhancement in a similar location after gadolinium (white arrow). **(7C)** demonstrates restricted diffusion in the ADC map for the lesion (white arrow). **(7D)** demonstrates some very tiny calcifications, which can be worked around with the TULSA device (white arrowhead). (Unpublished data)



8 Summary images from the MRI-guided TULSA treatment. The first row shows the T2-weighted anatomic images corresponding to the location of the individual US transducers from E2–E7. The second row shows the maximal heat delivered by each US transducer at each level. The third row shows the calculated damage map based on the Arrhenius equation. The fourth row shows the postgadolinium images after the ablation, confirming the treatment zone at each level. (Unpublished data)

Hepatobiliary

Image-guided thermal ablation is considered a curative-intent treatment for very early or early stage hepatocellular carcinoma (HCC) [29]. Additionally, thermal ablation is used for treatment of a wide range of metastases to the liver, particularly colorectal liver metastases (CRLM) [30]. Historically, US and CT were the most common imaging modalities used for guidance and monitoring during hepatic radiofrequency or microwave ablation [31, 35]. However, in recent years, MRI-guided thermal ablation including RFA, MWA (Fig. 9), laser ablation, and cryo-ablation have emerged as safe and effective treatment options, particularly when the liver lesion is best visualized by MRI. We have found MRI guidance and monitoring for ablation particularly useful for small hepatic tumors that are poorly visualized by ultrasound, and for tumors deep in the liver such as in the caudate lobe, high up in the hepatic dome, or adjacent to critical structures such as central bile ducts, stomach, or colon, where monitoring of the ablation zone is critical.



9 MRI-guided microwave ablation in a 72-year-old male for metastatic prostate cancer to the liver with central lesion. **(9A)** is the T2 weighted image demonstrating a small central lesion (orange arrow). **(9B)** shows the post-gadolinium image demonstrating delayed enhancement to the remaining liver typical of prostate cancer mets (orange arrow). **(9C)** demonstrates placement of the microwave antennae using a combination of US/MRI guidance (orange arrow). **(9D)** (phase imaging), **(9E)** (estimated damage map), and **(9F)** (T1 anatomic imaging) are from the temperature mapping proton resonance frequency imaging during the ablation. **(9D)** demonstrates the active temperature rise from the ablation (orange arrow). **(9E)** shows the damage map based on time and temperature change measurements using the Arrhenius equation (orange arrow). Followup MRI at three months post-ablation with **(9G)** (T2-weighted images), **(9H)** (pre-contrast T1 images), and **(9I)** (post-gadolinium images) demonstrating significant decrease in size since treatment consistent with evolving ablation changes. (Unpublished images)

Musculoskeletal and soft tissue

There has been an increasing role for image-guided thermal ablative therapies in the treatment of musculoskeletal and soft tissue tumors including the use of MRI guidance [36–38]. MRgFUS and cryoablation are feasible for treatment of focal metastatic disease to the bone. Additionally, several series have reported on the safety and effectiveness of percutaneous ablation for treatment of extra-abdominal desmoid tumors [39–41]. MRI-guided ablation is particularly beneficial when desmoid tumors are in close proximity to critical structures such as hollow viscus or nerves. Lastly, in patients with soft tissue oligometastatic disease, MRI-guided cryoablation offers a minimally invasive palliative treatment option [42, 43].

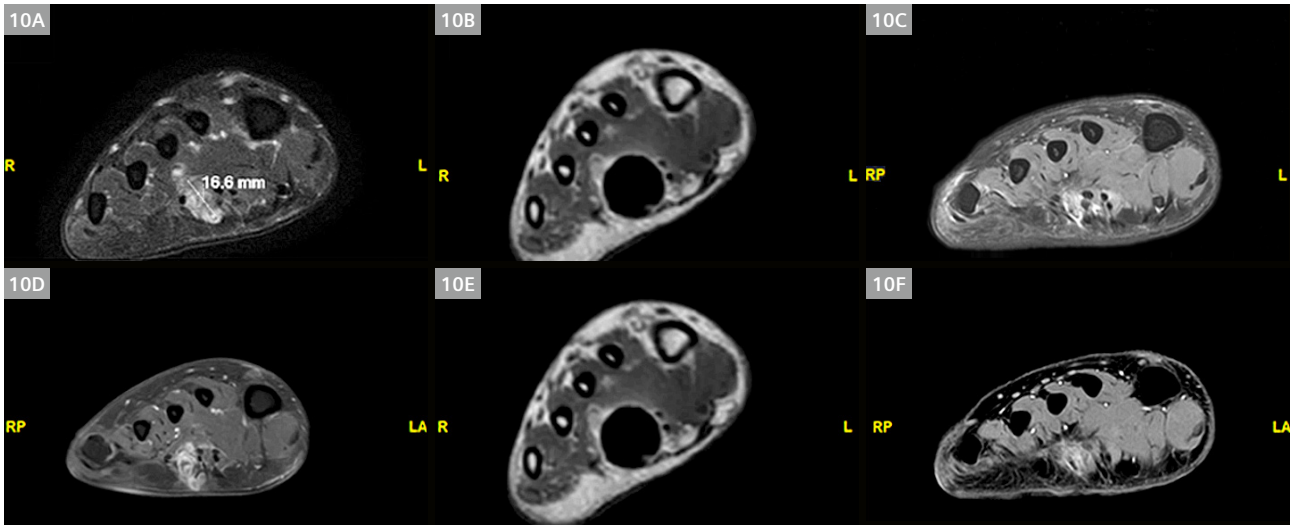
Peripheral soft tissue vascular anomalies

Peripheral soft tissue vascular anomalies (VA) include vascular tumors and vascular malformations. While percutaneous image-guided sclerotherapy and embolization are considered first-line treatments for symptomatic VA depending on size, location, and flow characteristics, emerging evidence suggests that MRI-guided laser ablation and cryoablation (Fig. 10) are safe and effective for treatment of symptomatic peripheral soft tissue VA [44–46]. In our practice, the most common vascular anomalies we treat with MRI-guided ablation include both pediatric and adult focal slow-flow venous or venolymphatic malformations, and focal vascular tumors, most commonly in the trunk or extremities. Less commonly, we have treated small focal high-flow arteriovenous malformations (AVMs) with MRI-guided ablation and a tourniquet proximal to the site of ablation to decrease the high flow, and focal cervicofacial slow-flow venous malformations.

Conclusions and future directions

Significant advancements in iMRI magnets, technology, and devices over the last three decades have enabled rapid growth of clinical body iMRI applications including lesion localization, biopsy, drainage, sclerotherapy, and ablation. Building a successful clinical iMRI practice requires

1. multidisciplinary collaboration and teamwork, including interventional and diagnostic radiologists, clinicians, MR physicists, technologists and nurses, anesthesiologists and nurse anesthetists, administrators and industry partners,
2. investment in personnel, space, equipment, and resources,
3. education of referring clinicians regarding the clinical safety and effectiveness of clinical body iMRI applications, particularly as a problem-solving tool when other image-guided procedures have failed or are deemed not technically feasible. Safety in the iMRI environment is paramount and requires close collaboration with MR physicists and MRI safety officers. Ongoing technological and technique advancements such as interventional PET/MRI, advanced navigation systems, and robotics will help interventional radiologists continue to push the frontiers of body iMRI applications in the coming decades [47, 48].



10 **(10A)** demonstrates high T2 signal in the plantar aspect of the foot, representing a slow-flow vascular malformation causing significant pain to the patient every day when walking. **(10D)** demonstrates the gadolinium enhancement within the vascular malformation. **(10B)** and **(10E)** demonstrate the ice ball formation during the MRI-guided cryoablation. **(10C)** represents the postablation T2 signal change, which usually decreases significantly. **(10F)** represents the postablation gadolinium lack of enhancement consistent with treatment and no flow. (Unpublished images)

References

1 Thompson SM, Gorny KR, Koepsel EMK, Welch BT, Mynderse L, Lu A, et al. Body Interventional MRI for Diagnostic and Interventional Radiologists: Current Practice and Future Prospects. Radiographics. 2021;41(6):1785–801.
2 Mueller PR, Stark DD, Simeone JF, Saini S, Butch RJ, Edelman RR, et al. MR-guided aspiration biopsy: needle design and clinical trials. Radiology. 1986;161(3):605–9.
3 Lufkin R, Teresi L, Chiu L, Hanafee W. A technique for MR-guided needle placement. AJR Am J Roentgenol. 1988;151(1):193–6.
4 Duckwiler G, Lufkin RB, Teresi L, Spickler E, Dion J, Vinuela F, et al. Head and neck lesions: MR-guided aspiration biopsy. Radiology. 1989;170(2):519–22.
5 Sedaghat F, Tuncali K. Enabling Technology for MRI-Guided Intervention. Top Magn Reson Imaging. 2018;27(1):5–8.
6 Busse H, Kahn T, Moche M. Techniques for Interventional MRI Guidance in Closed-Bore Systems. Top Magn Reson Imaging. 2018;27(1):9–18.
7 Sequeiros RB, Ojala R, Kariniemi J, Perala J, Niinimaki J, Reinikainen H, et al. MR-guided interventional procedures: a review. Acta Radiol. 2005;46(6):576–86.
8 Weiss CR, Nour SG, Lewin JS. MR-guided biopsy: a review of current techniques and applications. J Magn Reson Imaging. 2008;27(2):311–25.
9 White MJ, Thornton JS, Hawkes DJ, Hill DLG, Kitchen N, Mancini L, et al. Design, operation, and safety of single-room interventional MRI suites: practical experience from two centers. J Magn Reson Imaging. 2015;41(1):34–43.
10 Nour SG, Lewin JS. Creating a Clinical Interventional MRI Service. Top Magn Reson Imaging. 2018;27(1):25–31.
11 Lu A, Woodrum DA, Felmlee JP, Favazza CP, Gorny KR. Improved MR-thermometry during hepatic microwave ablation by correcting for intermittent electromagnetic interference artifacts. Phys Med. 2020;71:100–107.
12 Gorny KR, Favazza CP, Lu A, Felmlee JP, Hangiandreou NJ, Browne JE, et al. Practical implementation of robust MR-thermometry during clinical MR-guided microwave ablations in the liver at 1.5 T. Phys Med. 2019;67:91–99.
13 Ma C, Long ZY, Lanners DM, Tradup DJ, Brunnquell CL, Felmlee JP, et al. Protocol for testing suitability of compact US imaging systems for use inside MRI suites, and application to one commercial US system. Biomed Phys Eng Expr. 2016;2(4).
14 Yutzy SR, Duerk JL. Pulse sequences and system interfaces for interventional and real-time MRI. J Magn Reson Imaging. 2008;27(2):267–75.
15 Kahn T, Busse H. Interventional magnetic resonance imaging. Heidelberg: Springer; 2012. xvii, pp. 496.
16 Kaye EA, Granlund KL, Morris EA, Maybody M, Solomon SB. Closed-Bore Interventional MRI: Percutaneous Biopsies and Ablations. AJR Am J Roentgenol. 2015;205(4):W400–10.
17 Lewin JS, Nour SG, Duerk JL. Magnetic resonance image-guided biopsy and aspiration. Top Magn Reson Imaging. 2000;11(3):173–83.
18 Nour SG, Lewin JS. Percutaneous biopsy from blinded to MR guided: an update on current techniques and applications. Magn Reson Imaging Clin N Am. 2005;13(3):441–64.
19 Thompson SM, Gorny KR, Jondal DE, Rech KL, Mardini S, Woodrum DA. MRI-guided Wire Localization Surgical Biopsy in an Adolescent Patient with a Difficult to Diagnose Case of Lymphoma. Cardiovasc Intervent Radiol. 2017;40(1):135–138.
20 Tuen VC, Zingula SN, Moir C, Reed AM, Matsumoto JM, Woodrum DA. MRI guided wire localization muscle biopsy in a child with juvenile dermatomyositis. Pediatr Rheumatol Online J. 2013;11(1):15.
21 O'Mara DM, Berges AJ, Fritz J, Weiss CR. MRI-guided percutaneous sclerotherapy of venous malformations: initial clinical experience using a 3T MRI system. Clin Imaging. 2020;65:8–14.
22 Andreisek G, Nanz D, Weishaupt D, Pfammatter T. MR imaging-guided percutaneous sclerotherapy of peripheral venous malformations with a clinical 1.5-T unit: a pilot study. J Vasc Interv Radiol. 2009;20(7):879–87.
23 Woodrum DA, Gorny KR, Greenwood B, Mynderse LA. MRI-Guided Prostate Biopsy of Native and Recurrent Prostate Cancer. Semin Intervent Radiol. 2016;33(3):196–205.
24 Woodrum DA, Gorny KR, Mynderse LA. MR-Guided Prostate Interventions. Top Magn Reson Imaging. 2018;27(3):141–151.
25 Woodrum DA, Kawashima A, Gorny KR, Mynderse LA. Targeted prostate biopsy and MR-guided therapy for prostate cancer. Abdom Radiol (NY). 2016;41(5):877–88.
26 Atwell TD, Schmit GD, Boorjian SA, Mandrekar J, Kurup AN, Weisbrod AJ, et al. Percutaneous ablation of renal masses measuring 3.0 cm and smaller: comparative local control and complications after radiofrequency ablation and cryoablation. AJR Am J Roentgenol. 2013;200(2):461–6.
27 Thompson SM, Schmitz JJ, Thompson RH, Weisbrod AJ, Welch BT, Viers BR, et al. Introduction of Microwave Ablation Into a Renal Ablation Practice: Valuable Lessons Learned. AJR Am J Roentgenol. 2018;211(6):1381–1389.
28 Cazzato RL, De Marini P, Leonard-Lorant I, Leclerc L, Auloge P, Tricard T, et al. Safety and Oncologic Outcomes of Magnetic Resonance Imaging-Guided Cryoablation of Renal Cell Carcinoma: A 10-Year Single-Center Experience. Invest Radiol. 2021;56(3):153–162.
29 Weinstein JL, Ahmed M. Percutaneous Thermal Ablation for Hepatocellular Carcinoma. Semin Intervent Radiol. 2020;37(5):527–536.
30 Ruers T, Van Coevorden F, Punt CJ, Pierie JE, Borel-Rinkes I, Ledermann JA, et al. Local Treatment of Unresectable Colorectal Liver Metastases: Results of a Randomized Phase II Trial. J Natl Cancer Inst. 2017;109(9):djx015.
31 Yang N, Gong J, Yao L, Wang C, Chen J, Liu J, et al. Magnetic resonance imaging-guided microwave ablation of hepatic malignancies: Feasibility, efficacy, safety, and follow-up. J Cancer Res Ther. 2020;16(5):1151–1156.
32 Xiang J, Liu M, Lu R, Wang L, Xu Y, He X, et al. Magnetic resonance-guided ablation of liver tumors: A systematic review and pooled analysis. J Cancer Res Ther. 2020;16(5):1093–1099.
33 Winkelmann MT, Gohla G, Kubler J, Weiss J, Clasen S, Nikolaou K, et al. MR-Guided High-Power Microwave Ablation in Hepatic Malignancies: Initial Results in Clinical Routine. Cardiovasc Intervent Radiol. 2020;43(11):1631–1638.
34 Weiss J, Winkelmann MT, Gohla G, Kubler J, Clasen S, Nikolaou K, et al. MR-guided microwave ablation in hepatic malignancies: clinical experiences from 50 procedures. Int J Hyperthermia. 2020;37(1):349–355.
35 Chen J, Lin Z, Lin Q, Lin R, Yan Y, Chen J. Percutaneous radiofrequency ablation for small hepatocellular carcinoma in hepatic dome under MR-guidance: clinical safety and efficacy. Int J Hyperthermia. 2020;37(1):192–201.
36 Ahrar K, Sabir SH, Yevich SM, Sheth RA, Ahrar JU, Tam AL, et al. MRI-Guided Interventions in Musculoskeletal System. Top Magn Reson Imaging. 2018;27(3):129–139.
37 Nour SG, Monson DK. MRI-guided musculoskeletal soft tissue interventions. Top Magn Reson Imaging. 2011;22(4):197–205.
38 Kurup AN, Callstrom MR. Increasing Role of Image-Guided Ablation in the Treatment of Musculoskeletal Tumors. Cancer J. 2016;22(6):401–410.

39 Griffin MO, Kulkarni NM, O'Connor SD, Sudakoff GS, Lea WB, Tutton SM. Magnetic Resonance-Guided Focused Ultrasound: A Brief Review With Emphasis on the Treatment of Extra-abdominal Desmoid Tumors. Ultrasound Q. 2019;35(4):346–354.
40 Havez M, Lippa N, Al-Ammari S, Kind M, Stoeckle E, Italiano A, et al. Percutaneous image-guided cryoablation in inoperable extra-abdominal desmoid tumors: a study of tolerability and efficacy. Cardiovasc Intervent Radiol. 2014;37(6):1500–6.
41 Schmitz JJ, Schmit GD, Atwell TD, Callstrom MR, Kurup AN, Weisbrod AJ, et al. Percutaneous Cryoablation of Extraabdominal Desmoid Tumors: A 10-Year Experience. AJR Am J Roentgenol. 2016;207(1):190–5.
42 Vaswani D, Wallace AN, Eiswirth PS, Madaelil TP, Chang RO, Tomasian A, et al. Radiographic Local Tumor Control and Pain Palliation of Sarcoma Metastases within the Musculoskeletal System with Percutaneous Thermal Ablation. Cardiovasc Intervent Radiol. 2018;41(8):1223–1232.
43 McMenomy BP, Kurup AN, Johnson GB, Carter RE, McWilliams RR, Markovic SN, et al. Percutaneous cryoablation of musculoskeletal oligometastatic disease for complete remission. J Vasc Interv Radiol. 2013;24(2):207–13.
44 Thompson SM, Callstrom MR, McKusick MA, Woodrum DA. Initial Results of Image-Guided Percutaneous Ablation as Second-Line Treatment for Symptomatic Vascular Anomalies. Cardiovasc Intervent Radiol. 2015;38(5):1171–8.
45 Cornelis FH, Labreze C, Pinsolle V, Le Bras Y, Castermans C, Bader C, et al. Percutaneous Image-Guided Cryoablation as Second-Line Therapy of Soft-Tissue Venous Vascular Malformations of Extremities: A Prospective Study of Safety and 6-Month Efficacy. Cardiovasc Intervent Radiol. 2017;40(9):1358–1366.
46 Cornelis FH, Marin F, Labreze C, Pinsolle V, Le Bras Y, Midy D, et al. Percutaneous cryoablation of symptomatic venous malformations as a second-line therapeutic option: a five-year single institution experience. Eur Radiol. 2017;27(12):5015–5023.
47 Reich CM, Sattler B, Jochimsen TH, Unger M, Melzer L, Landgraf L, et al. Practical setting and potential applications of interventions guided by PET/MRI. Q J Nucl Med Mol Imaging. 2020;65(1):43–50.
48 Hata N, Moreira P, Fischer G. Robotics in MRI-Guided Interventions. Top Magn Reson Imaging. 2018;27(1):19–23.

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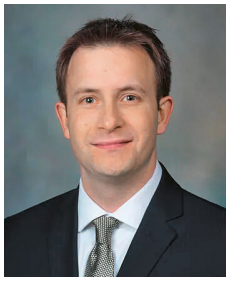

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Interventional MRI in the Liver: Why, When, and Where?

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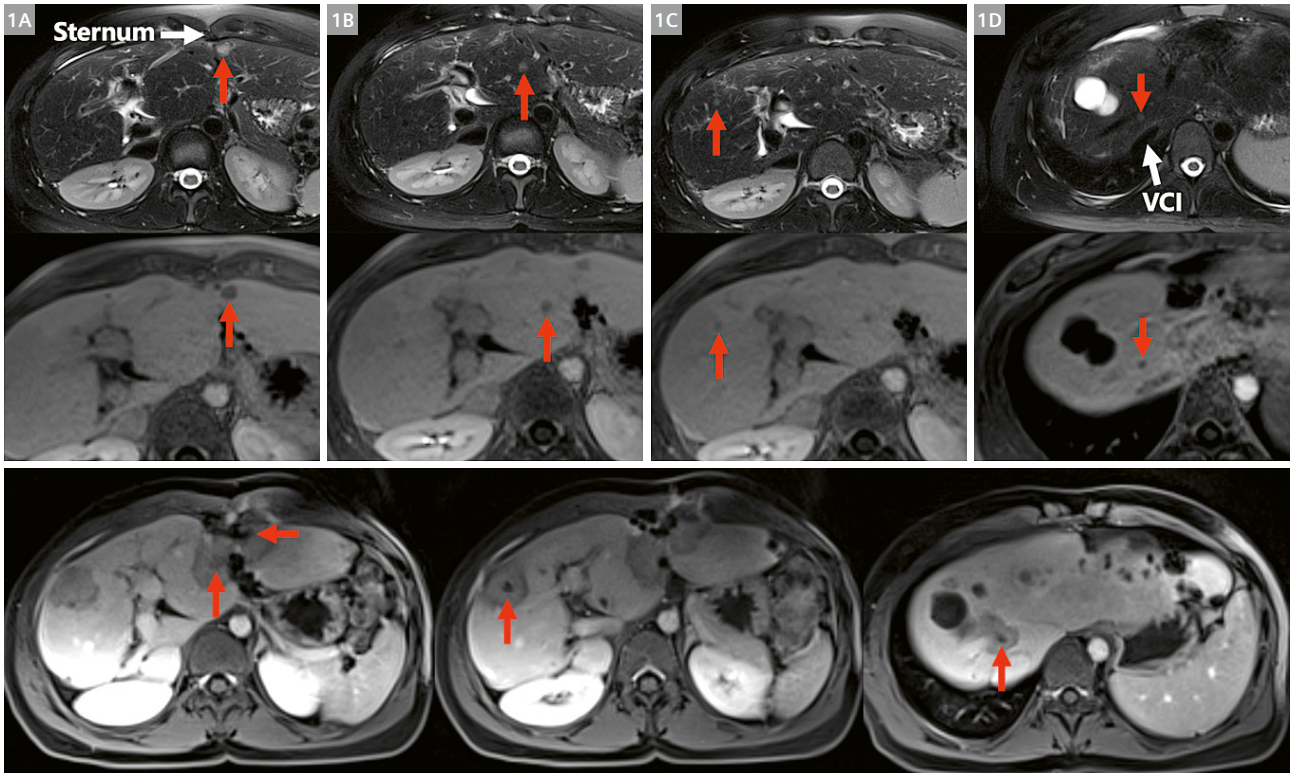
Introduction

Liver cancer is one of the fastest-growing types of cancer and a significant contributor to cancer-related mortality with a rising incidence [1, 2]. Minimally invasive non-surgical local liver therapies have a central role to play in appropriately selected patients with hepatobiliary cancer. Given the multitude of therapeutic options available, hepatobiliary cancer patients should be assessed by the multidisciplinary tumor board of a center where all therapeutic options, including local and locoregional tumor therapies, are available, along with advanced imaging technology.

Ultrasound (US), computed tomography (CT), and fluoroscopic-guided hepatobiliary interventions have been widely accepted in clinical practice for many years. However, as noted in the CIRSE guidelines, they present challenges such as radiation exposure, limited field of



1 Ablation of small liver lesions in challenging tumor locations.
A 24-year-old female patient with long-standing multifocal hepatocellular carcinoma (HCC) and peritoneal metastasis underwent various treatments, including hemihepatectomy, atypical resection, chemotherapy/immunotherapy, transarterial chemoembolization (TACE), and radiation therapy. The chemotherapy/immunotherapy regimen effectively reduced the size of the four remaining liver lesions. These lesions were selected for MRI-guided microwave ablation due to their small size (< 1 cm) and the superior visualization provided by MRI. Additionally, multiplanar imaging facilitated access to challenging locations, including one lesion behind the sternum **(1A)** and another near the vena cava inferior (VCI) **(1D)**.

view (FOV), and difficulties in visualizing targets close to sensitive anatomy [3]. Ongoing research aims to enhance imaging techniques and improve fusion methods to overcome these limitations. While image fusion offers promise for future interventions, it remains complex and time-consuming, and requires specialized expertise, with current software often lacking ease-of-use and compatibility across different imaging systems. Additionally, it can be unreliable in regions affected by complex organ movement, e.g., the liver [4].

Magnetic resonance imaging (MRI) offers a compelling solution for liver interventions by providing multiplanar real-time needle guidance without exposure to ionizing radiation. It has excellent soft tissue contrast and outstanding spatial and temporal resolution, along with functional imaging capabilities like diffusion-weighted imaging. Additionally, real-time temperature measurement during liver ablation helps to ensure complete tumor destruction while preserving surrounding healthy tissue and thus minimizing collateral damage [5–10].

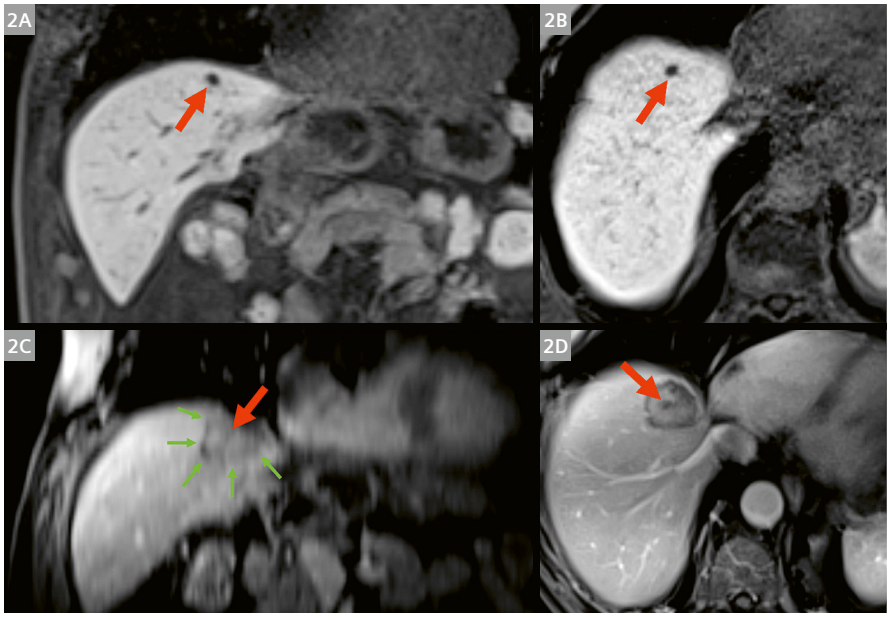
Why use MRI for liver interventions?

Superior imaging capabilities

MRI-guided liver interventions benefit from high-resolution real-time visualization for navigating through complex liver anatomy. This is particularly relevant when traditional imaging techniques like CT and US fail to display small structures such as small tumors or bile ducts. In these scenarios, conventional imaging techniques often rely on anatomical landmarks. A key advantage of MRI is its ability to safely and accurately delineate small targets, such as small liver tumors, bile ducts, and vascular structures (Fig. 1).

Access to challenging anatomical areas

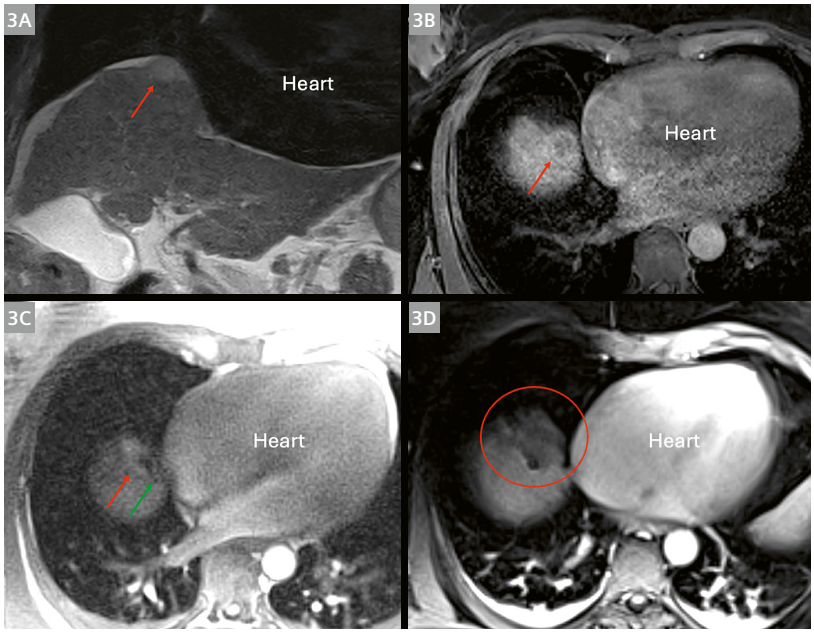
MRI is particularly useful for interventions in challenging liver regions, such as the liver dome (Fig. 2) or close to the heart (Fig. 3). In these regions, the lung can severely limit the FOV in ultrasound, making target visualization difficult or impossible. CT-guided interventions face challenges due to steep angles that need to be navigated to avoid lung tissue during puncture. The advanced 3D imaging capability offered by MRI is instrumental in safely and precisely operating near critical structures. It enables double oblique angulations when advancing interventional devices. Multiple targets can be easily accessed from the same entry point. This reduces the number of transitions through the liver capsule, which are painful and increase the risk of bleeding. It potentially reduces the procedure time by reducing the need for repositioning the surface coil and sterile drape.



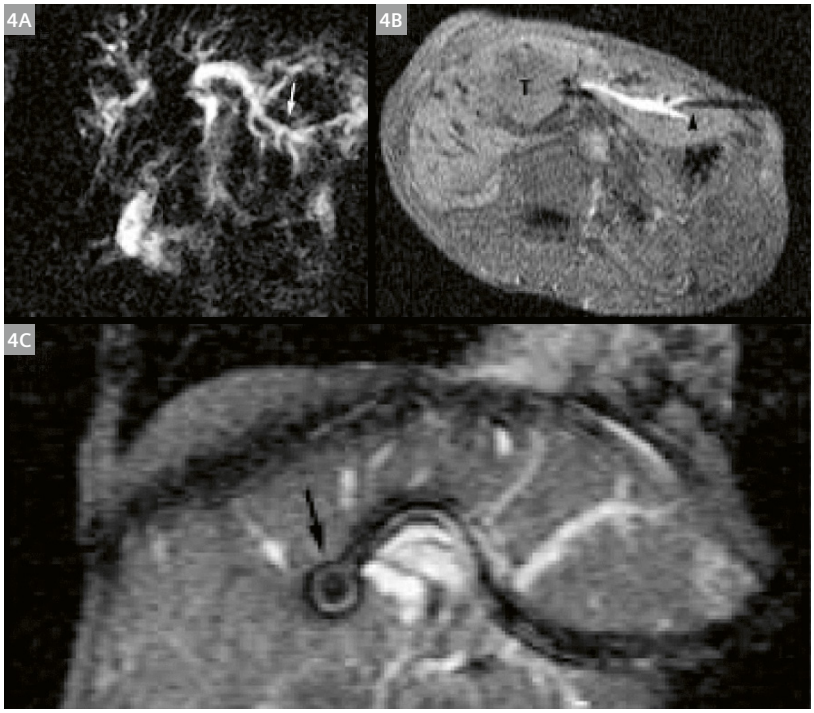
2 Ablation of a small liver lesion next to the diaphragm. A 76-year-old male patient with a history of metastatic rectal carcinoma, previously treated with hemicolectomy, rectal amputation, hemihepatectomy, liver ablation, and radiochemotherapy. Subsequent imaging detected three new liver tumors, including a small lesion (7 mm; red arrow) just 5 mm below the diaphragm. Pre-ablation T1-weighted imaging (**2A**: coronal; **2B**: axial) showing the lesion, which is challenging to treat due to its small size and its location where liver movement is most pronounced. Post-ablation T1-weighted imaging (**2C**: reformatted coronal; **2D**: axial) demonstrates complete ablation including sufficient safety margins (green arrow).

Radiation-free visualization for percutaneous transhepatic biliary drainage

Percutaneous transhepatic biliary drainage, also known as percutaneous transhepatic cholangiodrainage (PTCD) is usually performed fluoroscopically by inserting a fine needle into a peripheral bile duct. However, bile ducts are not visible with X-rays, and can also be difficult to target with US when not dilated. Consequently, fluoroscopically guided PTCD exposes the interventionalists and patients to substantial radiation. MRI offers a safer alternative [11, 12] by enabling direct visualization of these ducts without radiation exposure, even using a low-field MRI system [13] (Fig. 4). This facilitates precise targeting and reduces the burden of radiation exposure, benefiting safety for both patients and interventionalists in the long term.



3 **Ablation of a liver lesion next to the heart**
A patient with Child-Pugh B liver cirrhosis caused by non-alcoholic fatty liver disease presented with a lesion (15 × 10 × 13 mm) suspicious for hepatocellular carcinoma (HCC) in Liver Segment 8. Coronal T2-weighted imaging **(3A)** and T1-weighted post-contrast imaging **(3B)** reveal the tumor (red arrow), demonstrating typical washout following gadolinium administration. Given the challenging exophytic location of the lesion near the heart and diaphragm, the multidisciplinary tumor board opted for an MRI-guided liver biopsy and ablation in the same session. A coaxial technique with two probes was employed for the biopsy, which confirmed the diagnosis of HCC (not shown). Subsequently, MRI-guided microwave ablation[1] was performed. T1-weighted imaging **(3C)** confirmed the position of the antenna at the center of the lesion (green arrow). T1-weighted post-contrast imaging **(3D)** demonstrated complete tumor ablation.



4 **First in-human MRI-guided percutaneous biliary drainage.**
Cholestasis patient with central colorectal carcinoma metastasis:
(4A) Oblique coronal MR cholangiography helps identify the optimal access path for percutaneous puncture of the dilated bile ducts in the left liver lobe (arrow).
(4B) Axial T1-weighted image (FLASH sequence, 110/9 ms, 808) after the puncture and injection of diluted paramagnetic contrast agent into the bile ducts of the left liver lobe, clearly showing the needle (arrowhead) and a central tumor (T).
(4C) Frames from the continuously acquired T2-weighted image series (TrueFISP sequence, 12.5/5.9 ms, 80°) monitoring the guidewire insertion and catheter advancement, with the guidewire tip (arrow) and catheter located in the central bile ducts.
Figure reprinted with courtesy of Thieme Verlag: Wacker F et al. (2000) MR imaging-guided biliary drainage in an open low-field system: First clinical experiences.

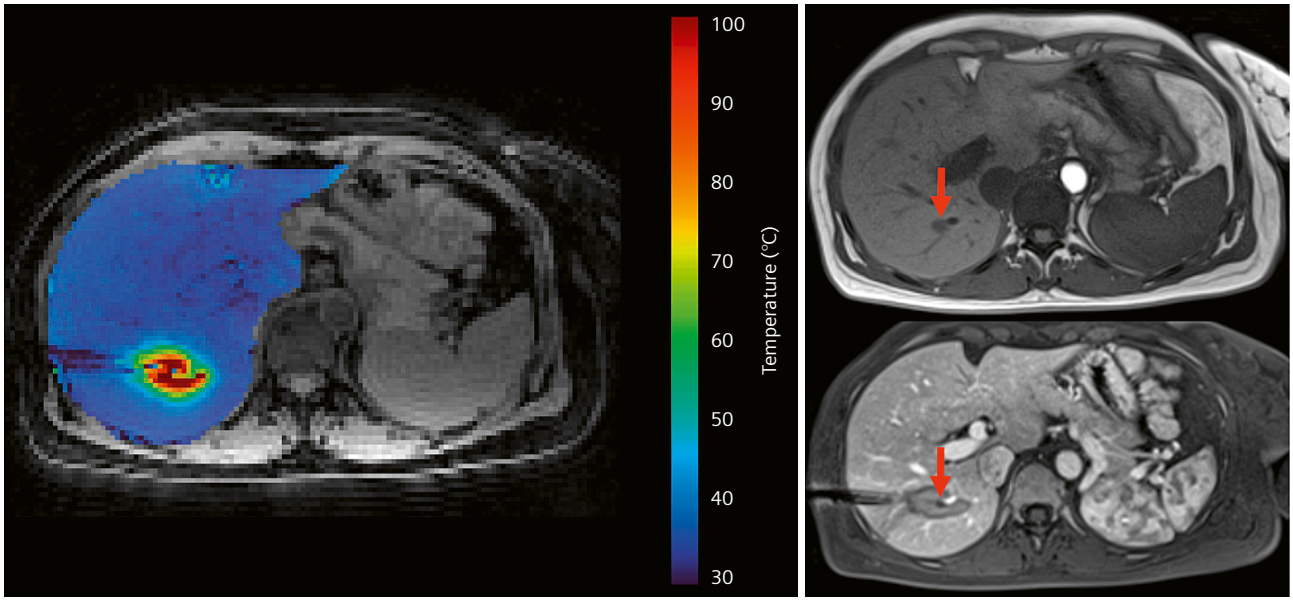
MR thermometry during microwave ablation[1]

The temperature distribution during ablation is influenced by factors such as tissue-specific absorption and perfusion, which can be compromised by prior surgeries, systemic therapies or radiation, and the presence of adjacent vessels (known as the heatsink effect [14]). Unlike CT- and US-guided ablation, which lack temperature control, MRI enables real-time, non-invasive temperature measurements during ablation [15, 16] (Fig. 5). This capability provides immediate, non-invasive feedback on ablation effectiveness, allowing for necessary adjustments to optimize the ablation zone and ensure complete tumor destruction. This precision is crucial for minimizing tumor recurrence and complications. MR thermometry relies on temperature-dependent shifts in the proton resonance frequency (PRF) to accurately map temperature distributions within liver tissue [17–19]. Due to respiratory motion and the heterogeneous nature of the liver, advanced motion correction and fat suppression techniques are often required to ensure precise measurements. The temperature distribution can then be interpreted through a model to predict cell death [20].

When and where should MRI be used for liver interventions?

Liver biopsies

Liver biopsies (LB) are a routine diagnostic tool in clinical practice, often performed with US or CT guidance. Depending on the location and the size of the liver lesion, MRI guidance can help to increase the accuracy of these biopsies. In the era of personalized medicine, the need to analyze genetic material of tumor cells and surrounding tissue is constantly increasing in order to guide personalized treatment strategies, provide prognostic insights, and monitor responses to therapy [21, 22]. Genomic profiling demands highly precise and repeated biopsies to accurately differentiate between viable tumor cells and inflammatory changes. Here, MRI can offer unique information to improve exact targeting. This is especially important during treatment, when the liver tumors may be small and show mixed responses, and inaccurate biopsies can directly affect patient treatment.



5 **Thermometry of a microwave ablation[1] in the liver showing the heat sink effect.**
A 49-year-old female patient with liver metastasis from colon cancer underwent a left-sided hemicolectomy along with resection of liver segments 2 and 6. During follow-up, a single metastasis was identified in Liver Segment 7 (red arrow). Due to its size and location, this lesion was selected for MRI-guided treatment. Microwave ablation was performed for seven minutes at 120 Watts, with continuous monitoring of the temperature using proton resonance frequency shift (PRFS) thermometry. The heat distribution effectively covered the entire tumor, aligning with the ablation zone shown on post-contrast T1-weighted imaging. Notably, a heat sink effect was observed near an adjacent vessel.

[1] *The information presented herein refers to an application developed independently by a third party and is not a product of Siemens Healthineers. The regulatory compliance of this application remain the sole responsibility of the respective institution.*

Liver ablation

Percutaneous tumor ablation (PTA) is increasingly accepted, both in combination with other therapies and as a stand-alone treatment. Most (≥ 70%) patients are not candidates for surgical resection or liver transplantation due to comorbidities or advanced disease stages [23–25]. In these cases, PTA as a first-line therapy offers significant advantages, such as effective tumor growth control, reduced recurrence rates, and a more favorable safety profile with lower morbidity and mortality compared to surgery [26, 27].

Importantly, while the ablation of larger tumors historically led to higher recurrence rates [28], it is crucial to interpret these outcomes in the context of the initial role of PTA as a second-line treatment often used for larger tumors. However, recent developments have shifted this perspective.

A recent Phase III study (the COLLISION Trial) enrolled 295 patients with small colorectal cancer liver metastases (≤ 3 cm) and compared PTA to surgical resection [26, 27]. The trial was terminated early due to substantially higher mortality in surgery (2.1%; n = 3) versus PTA (n = 0). At 28.8 months, overall survival rates between the two groups showed no significant difference. However, PTA demonstrated numerous benefits over surgery, including fewer adverse events ($p < 0.001$), shorter hospitalization (median 1 day [range 1–44] vs. 4 days [range 1–36], $p < 0.001$), and improved local tumor control (hazard ratio 0.184; 95% confidence interval, 0.040–0.838; $p = 0.029$). The study concluded that PTA should be favored over surgery in patients with small colorectal liver metastases, because it better balances morbidity and mortality relative to similar oncologic outcomes.

Nonetheless, the optimal management of small liver tumors is still debated, with arguments saying that the individual tumor characteristics, tumor location, and the risk of complications must be considered when choosing between surgery and ablation [29]. Indeed, small liver tumors can be poorly visualized on CT or US imaging, which makes ablation challenging. Therefore, incorporating MRI guidance into the treatment algorithm for smaller tumors could potentially enhance the oncologic outcomes of PTA, offering a more precise and effective approach.

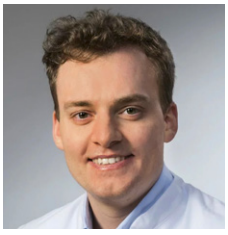
Conclusion

The integration of MRI guidance into hepatobiliary cancer diagnosis and treatment represents a significant advancement in interventional oncology. MRI provides high-resolution imaging, real-time needle placement, and real-time temperature monitoring. Its unique qualities enhance precise and safe planning, execution and monitoring of liver biopsies, liver tumor ablation, and percutaneous biliary drainage. With the ongoing development of MRI technology, research will continue to define new roles for MRI-guided procedures in the liver. Challenges of MRI-guided interventions that still need to be addressed include specialized interventional devices, hardware (e.g., communication systems), and software that enables ease of use and can support doctors who want to integrate interventional MRI into their practice more effectively. In order to advance this exciting technology, prospective multicenter studies with standardized research protocols and homogenous patient populations are needed.

References

1 Anwanwan D, Singh SK, Singh S, Saikam V, Singh R. Challenges in liver cancer and possible treatment approaches. Biochim Biophys Acta Rev Cancer. 2020;1873(1):188314.
2 Siegel RL, Miller KD, Jemal A. Cancer statistics, 2019. CA Cancer J Clin. 2019;69(1):7–34.
3 Veltri A, Bargellini I, Giorgi L, Almeida PAMS, Akhan O. CIRSE Guidelines on Percutaneous Needle Biopsy (PNB). Cardiovasc Intervent Radiol. 2017;40(10):1501–1513.
4 Basu S, Singhal S, Singh D. A Systematic Literature Review on Multimodal Medical Image Fusion. Multimed Tools Appl. 2024;83:15845–15913.
5 Öcal O, Dietrich O, Lentini S, Bour P, Faller T, Ozenne V, et al. Predicting liver ablation volumes with real-time MRI thermometry. JHEP Rep. 2024;6(11):101199.
6 Gorny KR, Favazza CP, Lu A, Felmlee JP, Hangiandreou NJ, Browne JE, et al. Practical implementation of robust MR-thermometry during clinical MR-guided microwave ablations in the liver at 1.5 T. Phys Med. 2019;67:91–99.
7 Lin Z, Chen J, Yan Y, Chen J, Li Y. Microwave ablation of hepatic malignant tumors using 1.5T MRI guidance and monitoring: feasibility and preliminary clinical experience. Int J Hyperthermia. 2019;36(1):1216–1222.
8 Lu A, Woodrum DA, Felmlee JP, Favazza CP, Gorny KR. Improved MR-thermometry during hepatic microwave ablation by correcting for intermittent electromagnetic interference artifacts. Phys Med. 2020;71:100–107.
9 Rosenberg C, Kickhefel A, Mensel B, Pickartz T, Puls R, Roland J, et al. PRFS-based MR thermometry versus an alternative T1 magnitude method--comparative performance predicting thermally induced necrosis in hepatic tumor ablation. PLoS One. 2013;8(10):e78559.
10 Zhu M, Sun Z, Ng CK. Image-guided thermal ablation with MR-based thermometry. Quant Imaging Med Surg 2017;7(3):356–368.
11 Wacker F, Branding G, Wagner A, Ewert A, Faiss S, Wendt M, et al. MRT-gestützte Gallenwegsdrainage: Erprobung der passiven Katheterdarstellung an einem Tiermodell [MRI-assisted bile duct drainage: evaluation of passive catheter imaging in an animal model]. Rofo. 1998;169(6):649–54. German.
12 Faiss S, Zeitz M, Wolf KJ, Lewin JS, Wacker FK. Magnetic resonance-guided biliary drainage in a patient with malignant obstructive jaundice and thrombocytopenia. Endoscopy. 2003;35(1):89–91.

13 Wacker F, Branding G, Zimmer T, Faiss S, Wolf KJ. MR-Cholangiopankreatikographie am offenen Niederfeldsystem bei 0.2 Tesla: Erste klinische Ergebnisse im Vergleich zum Hochfeldsystem (1.5 Tesla) und zur ERCP [MR cholangiopancreatography using an open low field system of 0.2 tesla: early clinical results compared with a high field system (1.5 tesla) and ERCP]. Rofo. 1997;167(6):579–84. German.
14 Ringe KI, Lutat C, Rieder C, Schenk A, Wacker F, Raatschen HJ. Experimental Evaluation of the Heat Sink Effect in Hepatic Microwave Ablation. PLoS One. 2015;10(7):e0134301.
15 Alpers J, Hensen B, Rötzer M, Reimert DL, Gerlach T, Vick R, et al. Comparison study of reconstruction algorithms for volumetric necrosis maps from 2D multi-slice GRE thermometry images. Sci Rep. 2022;12(1):11509.
16 Alpers J, Rötzer M, Gutberlet M, Wacker F, Hensen B, Hansen C. Adaptive simulation of 3D thermometry maps for interventional MR-guided tumor ablation using Pennes' bioheat equation and isotherms. Sci Rep. 2022;12(1):20356.
17 Parker DL. Applications of NMR imaging in hyperthermia: an evaluation of the potential for localized tissue heating and noninvasive temperature monitoring. IEEE Trans Biomed Eng. 1984;31(1):161–7.
18 Ishihara Y, Calderon A, Watanabe H, Okamoto K, Suzuki Y, Kuroda K, et al. A precise and fast temperature mapping using water proton chemical shift. Magn Reson Med. 1995;34(6):814–23.
19 Kägebein U, Speck O, Wacker F, Hensen B. Motion Correction in Proton Resonance Frequency-based Thermometry in the Liver. Top Magn Reson Imaging. 2018;27(1):53–61.
20 Schröer S, Alpers J, Gutberlet M, Brüsch I, Rumpel R, Wacker F, et al. A probabilistic thermal dose model for the estimation of necrosis in MR-guided tumor ablations. Med Phys. 2024;51(1):239–250.
21 Wood-Trageser MA, Lesniak AJ, Demetris AJ. Enhancing the Value of Histopathological Assessment of Allograft Biopsy Monitoring. Transplantation. 2019;103(7):1306–1322.
22 Wheler JJ, Janku F, Naing A, Li Y, Stephen B, Zinner R, et al. Cancer Therapy Directed by Comprehensive Genomic Profiling: A Single Center Study. Cancer Res. 2016;76(13):3690–701.
23 Benson AB, D'Angelica MI, Abbott DE, Anaya DA, Anders R, Are C, et al. Hepatobiliary Cancers, Version 2.2021, NCCN Clinical Practice Guidelines in Oncology. J Natl Compr Canc Netw. 2021;19(5):541–565.
24 Wang H, Li W. Recent update on comprehensive therapy for advanced hepatocellular carcinoma. World J Gastrointest Oncol. 2021;13(8):845–855.
25 Pusceddu C, Mascia L, Ninniri C, Ballicu N, Zedda S, Melis L, et al. The Increasing Role of CT-Guided Cryoablation for the Treatment of Liver Cancer: A Single-Center Report. Cancers (Basel). 2022;14(12):3018.
26 Puijk RS, Ruarus AH, Vroomen LGPH, van Tilborg AAJM, Scheffer HJ, Nielsen K, et al. Colorectal liver metastases: surgery versus thermal ablation (COLLISION) - a phase III single-blind prospective randomized controlled trial. BMC Cancer. 2018;18(1):821.
27 van der Lei S, Puijk RS, Dijkstra M, Schulz HH, Vos DJW, De Vries JJJ, et al. Thermal ablation versus surgical resection of small-size colorectal liver metastases (COLLISION): an international, randomised, controlled, phase 3 non-inferiority trial. Lancet Oncol. 2025;26(2):187–199.
28 Groeschl RT, Pilgrim CH, Hanna EM, Simo KA, Swan RZ, Sindram D, et al. Microwave ablation for hepatic malignancies: a multiinstitutional analysis. Ann Surg. 2014;259(6):1195–200.
29 Kim BH. Surgical resection versus ablation for early hepatocellular carcinoma: The debate is still open. Clin Mol Hepatol. 2022;28(2):174–176.



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Establishing an MRI-Guided Intervention Service Using a 0.55T System: Initial Experiences and Workflow Development

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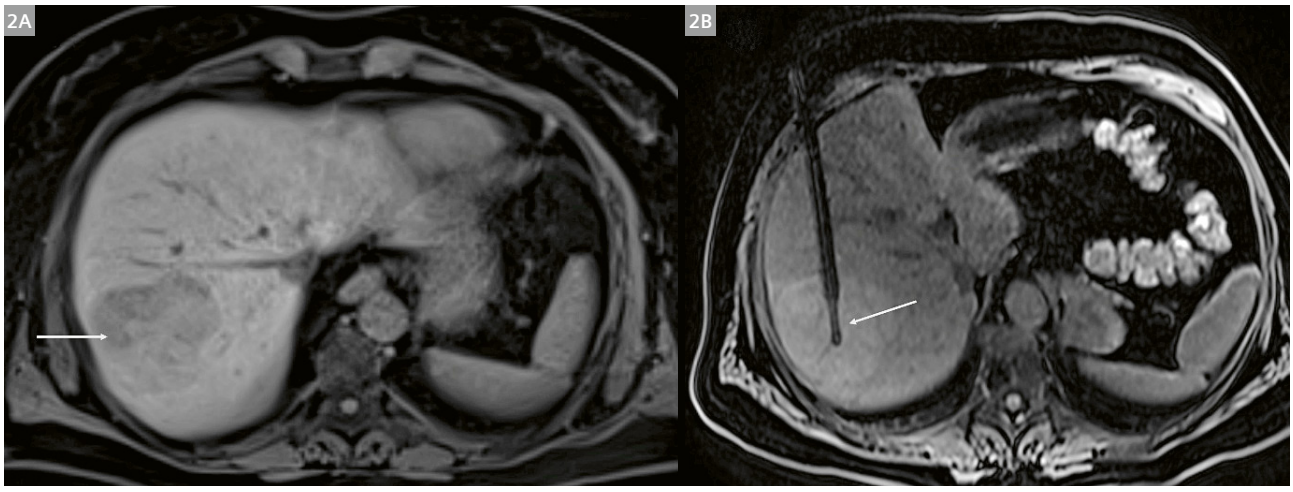
Introduction

Interventional radiology plays a crucial role in modern diagnostics and therapeutics. While computed tomography (CT) and ultrasound (US) guidance are well established for percutaneous needle-based procedures, certain clinical scenarios present challenges. Our radiology department has a robust program for CT-guided interventions, performing approximately 700 procedures annually, including biopsies, drainages, ablations, and pain management injections. Additionally, US-guided interventions are performed within the internal medicine department.

Despite this experience, we identified limitations that prompted improvements in our practice. Firstly, we encountered cases where lesions clearly visible on diagnostic MRI were poorly or not visualized under CT guidance, hindering successful biopsy. Secondly, concerns regarding cumulative radiation exposure, particularly in younger patients undergoing procedures like injection therapy for back pain, highlighted the need for non-ionizing imaging alternatives. Magnetic resonance imaging (MRI) guidance offers potential solutions by providing superior soft tissue contrast without ionizing radiation. Therefore, we embarked on establishing an MRI-guided intervention service "de novo". This manuscript details our initial experiences, the challenges encountered, workflow development, and key learnings during the implementation phase using a low-field 0.55T MRI system.

1 Image showing the operator during an MRI-guided biopsy. The needle is already advanced inside the liver, and the operator has to reach into the gantry to move the needle under live guidance or to stabilize the needle. Simultaneously, he has to rotate his head to see the in-room monitor placed on the opposite side of the table (not pictured). This position can be quite strenuous. On the other hand, this image shows how the 80 cm gantry provides ample space that allows a lot of freedom during the intervention.



2 A female patient with an incidentally detected liver lesion on a routine ultrasound examination. MRI showed a lesion with intermediate T2 hyperintensity and early contrast enhancement. Hepatobiliary contrast phase (**2A**, MRI performed at 1.5T) showed no or only little enhancement of the lesion (arrow). Thus, the diagnosis of focal nodular hyperplasia was deemed uncertain, and biopsy was proposed. T1 Dixon without contrast during MRI-guided biopsy **(2B)** clearly shows the extended biopsy needle inside the lesion (arrow). On histopathology, only normal liver tissue was found, which is consistent with the diagnosis of focal nodular hyperplasia.

Methods

Equipment and setup

The foundation of our service is a recently installed 0.55T MRI scanner (MAGNETOM Free.Max, Siemens Healthineers, Erlangen, Germany; software version *syngo* MR XA60). This system was chosen partly for its 80 cm bore diameter, which compared to standard bore magnets facilitates patient access during interventional procedures. The lower field strength (0.55T) was also anticipated to potentially reduce susceptibility artifacts caused by metallic instruments.

Following consultation with the vendor, the necessary software suite for MRI-guided interventions (Needle Intervention Add-in, Siemens Healthineers, Erlangen, Germany) was installed. An MRI-compatible in-room monitor (NordicNeuroLab, Bergen, Norway) was set up to allow visualization within the scanner room. A range of MRI-compatible needles (e.g., a 22-gauge needle from Innovative Tomography Products GmbH, Bochum, Germany) and biopsy devices (BIM 18-gauge biopsy needle and and corresponding coaxial guiding needles, Innovative Tomography Products GmbH, Bochum, Germany) were acquired.

Training

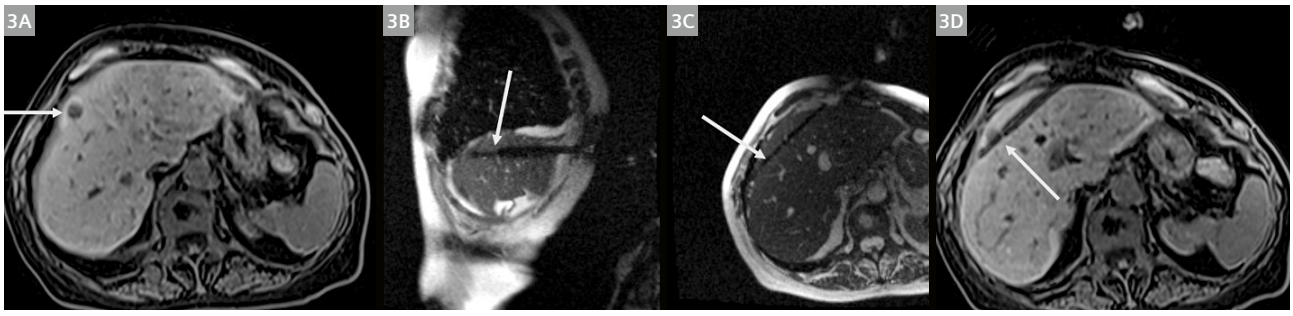
Initial training involved hands-on practice using MRI-compatible puncture phantoms (Triple Modality 3D Abdominal Phantom and Lumbar Training Phantom, Sun Nuclear, Melbourne, FL, USA). This phase allowed the team to familiarize themselves with the equipment, software interface, and various techniques for controlling and visualizing needle advancement. The capability for real-time needle tracking under MRI guidance was immediately recognized as a significant advantage. For initial training, we decided to keep the team limited (two senior radiologists, one junior radiologist, and three MRI technologists) to facilitate quicker adoption of internal team communication. We also had the opportunity to host MRI specialists from Siemens Healthineers, who helped us to optimize the interventional scan protocols for our needs.

MRI sequences

For pain injection therapy, a standard T2-weighted turbo spin echo (TSE) axial sequence was acquired for access planning. The main scan parameters of this sequence were: TE 106 ms; TR 2600 ms; flip angle 160°; bandwidth 100 Hz/pixel; number of averages 3; slice thickness 4 mm.

For abdominal biopsies, we used an axial T1 VIBE Dixon. The main scan parameters of this sequence were: TE 2.66 ms; TR 9.73 ms; flip angle 20°; bandwidth 333 Hz/pixel; number of averages 1; slice thickness 3 mm. This sequence was used for planning, intermittent control, and final check.

For live guidance, we used a BEAT IRT TRUFI sequence with the following parameters: TE 2.67 ms; TR 749.1 ms; flip angle 90°; bandwidth 668 Hz/pixel; number of averages 1; slice thickness 8 mm; acquisition plane axial and sagittal.



3 A female patient with a prior history of breast cancer. A CT examination showed multiple low-density liver lesions, and liver metastasis was suspected. Tissue sampling was needed for confirmation and therapy planning. Lesions were invisible on non-contrast CT imaging and difficult to distinguish even on contrast-enhanced CT imaging. Thus, MRI-guided biopsy was proposed. T1 Dixon without contrast **(3A)** clearly showed the lesion (arrow). **(3B)** and **(3C)** show the needle (arrow) in the real-time imaging. However, the lesion is hardly visible in these images. T1 Dixon **(3D)** performed with the needle held in place by the operator shows the biopsy needle positioned inside the target lesion (arrow). Histopathology was consistent with liver metastasis of the previously treated breast cancer.

Initial experiences and challenges

First clinical cases

We initiated clinical procedures with periradicular injections for pain management, perceiving these as relatively safe and technically straightforward introductions to in vivo MRI guidance. However, visualizing the fine-gauge needles (typically 21G or 22G) used for these injections proved challenging with the available interventional sequences, requiring careful technique and sequence optimization. Moreover, these interventions can usually be performed very quickly under CT guidance. While MRI can visualize nerve roots more clearly than CT, MRI is limited regarding the visualization of the articular space in facet joint blockade. Thus, we now tend to reserve this indication for young individuals.

Then we quickly moved to performing biopsies. We started with cases that had been unsuccessfully biopsied using CT guidance to demonstrate the feasibility of MRI-guided biopsy to target even lesions that were difficult to target under CT guidance.

MRI-guided biopsy challenges

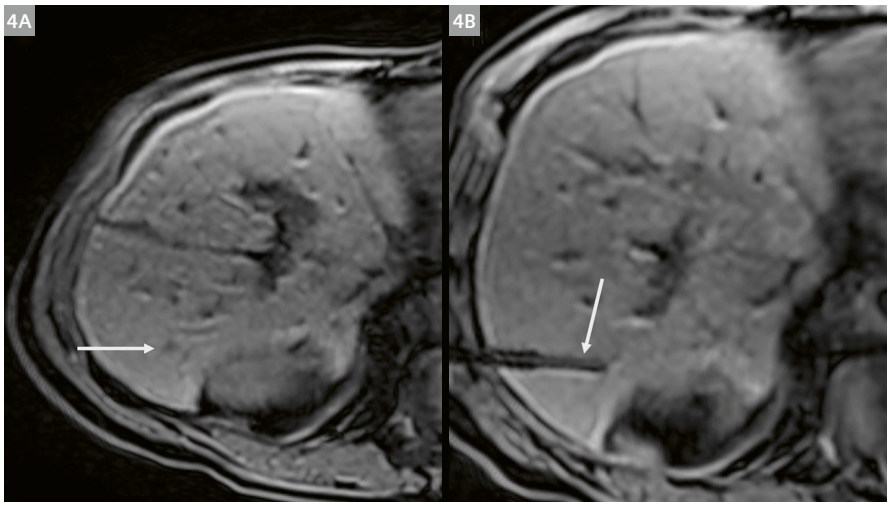
Performing MRI-guided biopsies, especially in the liver, introduced new challenges that were primarily related to respiratory motion and communication within the MRI environment.

- **Breathing motion:** Patient breathing significantly impacted procedures. Respiratory motion could displace the target lesion or the needle itself relative to the planned trajectory and the acquired imaging plane. This often necessitated interactive, real-time adjustments of the scan plane while simultaneously manipulating or stabilizing the needle. In some cases, this resulted in real-time sequences being only of limited use. Thus, we optimized a T1 Dixon sequence with a relatively short sequence time to use as an intermittent control sequence.
- **Communication:** The scanner environment inherently complicates communication between the operator at the patient's side and the MRI technician at the console. Additionally, the communication between the operator and the patient is also hindered, especially during real-time imaging. Giving clear breath-hold instructions while the scanner gradients are active is difficult.

Workflow development and solutions

Addressing the challenges required iterative refinement of our workflow and team communication strategies:

- **Team composition:** We found it highly beneficial to perform complex interventions with two radiologists experienced in percutaneous procedures. One radiologist focuses on needle manipulation and patient contact, while the second communicates with the MRI technician, adjusts imaging parameters, and provides overall procedural oversight. This division of labor proved effective, especially given the differing expertise levels – radiologists experienced in interventions but not in operating MRI consoles, and technicians experienced in MRI but not interventions.
- **Communication strategies:** Establishing clear and efficient communication was paramount. We observed that leaving the scanner room door ajar during non-scanning phases did not significantly degrade image quality in our low-field environment and greatly facilitated verbal communication. We also developed a system of non-verbal hand signals for use during scanning:

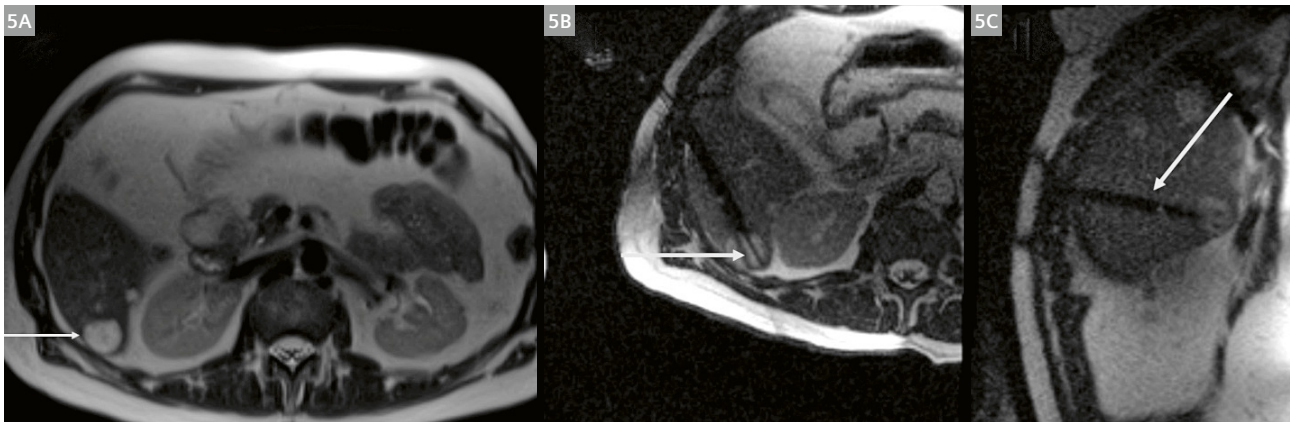


4 A male patient with an adenocarcinoma of the esophagus (stage T3 N+). During staging, MRI of the liver was performed and showed a small (5 mm) indeterminate liver lesion. Neoadjuvant chemotherapy and radiation therapy was performed, but the liver lesion persisted on restaging. MRI-guided biopsy was performed (arrow in **4A**: lesion on planning T1 Dixon). **(4B)** shows the biopsy needle inside the lesion (arrow). Histopathology ruled out liver metastasis, and the patient underwent surgery. Follow-up imaging showed an unchanged lesion consistent with benign origin.

  - **Thumbs-up:** Signal to start the scan sequence. Given during the sequence, it is a signal for the technician to adjust the scan plane to better visualize the needle tip.
  - **Raised flat hand:** Signal to immediately stop the current scan sequence.
- **Sequence selection:** For liver biopsies, particularly for lesions poorly visualized on CT, a T1-weighted Dixon sequence demonstrated excellent utility in depicting both the target lesion and the interventional needle, often enhanced by the sequence's inherent fat suppression. The near-isotropic voxel dimensions allow for effective multiplanar reformation (MPR) for trajectory evaluation. In select cases where lesion conspicuity remained insufficient, a liver-specific contrast agent (Gd-EOB-DTPA, Primovist, Bayer Vital, Leverkusen, Germany) was administered. While real-time sequences are invaluable for visualizing needle movement, they often lack the contrast resolution to clearly delineate the target lesion simultaneously. Therefore, our workflow frequently incorporates intermittent T1 Dixon acquisitions for definitive checks of needle position relative to the target. Using the MR View&Go workflow on the scanner allows for multiplanar reformations of this sequence, which is often needed especially when using out-of-plane puncture paths.
- **Skin entry point marking:** We initially experimented with various fluid-filled capsules and commercial MRI markers. However, our practice evolved towards a more direct method: using the radiologist's finger. The performing radiologist identifies the optimal entry point on the live images using their finger, holds it in place while the patient is moved out of the gantry, and marks the spot with a surgical pen before sterile preparation.

Current standardized workflow: Example with biopsy

1. **Patient positioning and coil setup:** The patient is positioned on the MRI table. Surface coils are placed over the target region, ensuring the anticipated puncture site remains accessible.
2. **Planning scan:** A diagnostic-quality scan (e.g., T1 Dixon, potentially pre- and post-contrast) is acquired to precisely localize the target lesion.
3. **Trajectory planning:** Using the MRI intervention software, the target lesion and desired skin entry point are marked, and the planned needle trajectory planes are defined.
4. **Entry point identification:** An interventional real-time sequence is initiated. The radiologist uses their index finger on the patient's skin, guided by the live images, to pinpoint the exact entry site corresponding to the planned trajectory.
5. **Marking and preparation:** The scan is stopped. The patient is carefully moved out of the gantry bore while the radiologist maintains finger pressure on the identified spot. The entry point is marked with a pen, surface coils are adjusted if necessary, and the area is prepped and draped using a sterile technique.
6. **Anesthesia and needle insertion:** Local anesthetic is administered. The biopsy needle (or introducer) is inserted through the marked entry point. The patient is moved back into the gantry, with the radiologist stabilizing the needle.
7. **Needle advancement and guidance:** The real-time sequence is restarted. The scan plane is adjusted as needed (using hand signals or verbal cues) to visualize the needle path. Breath-hold commands are given if required. The needle is advanced towards the target under imaging guidance.



5 A male patient who presented with multiple liver lesions and osteolytic bone lesions. Initially, multiple myeloma was suspected, but this was ruled out by bone marrow biopsy. Liver lesions appeared with high T2 signal and only minimal contrast enhancement. Planning T2 images showed the lesion (**5A**, arrow). BEAT IRE TRUFI real-time images (**5B** and **5C**) during the biopsy. **(5B)** shows the needle inside the lesion (arrow). This is not clearly seen on the second plane **(5C)**, due to the imperfect alignment of the needle and the scanning plane. Histopathology showed metastatic angiosarcoma.

8. **Confirmation and sampling:** Intermittent T1 Dixon scans are performed to confirm needle tip position relative to the target lesion. Adjustments are made under real-time guidance if necessary. Once the position is confirmed, biopsy sampling is performed according to standard technique. Based on operator preference, biopsy samples are taken through the trocar needle with or without additional imaging of the expanded biopsy system.
9. **Post-procedure:** After a satisfactory number and quality of biopsy samples have been taken, the needle is removed and a dressing is applied to the skin entry point. In cases where bleeding from the trocar needle is noted, needle tract embolization is performed using gel-foam cubes. Final imaging is performed to check for potential complications.

Despite the established workflow, several challenges remain.

Remaining challenges

- We have encountered difficulties with optimizing the workflow for efficient switching between real-time guidance for needle movement and intermittent T1 Dixon sequences for positional confirmation.
- The operator's body position during the intervention can be challenging, especially since needles tend to move due to breathing motion and need to be fixated by the operator. Thus, the operator needs to keep their hand and arm inside the gantry during scanning. This can require the operator to hold a strenuous body position for a prolonged time. We also noted that this is especially problematic for shorter operators, as they have limited arm reach, which may require them to position their upper torso inside the bore (see Fig. 1).
- Unlike the tools available for fluoroscopy and CT-guided interventions, the range of commercially available MRI-compatible tools is limited.
- In our practice, MRI-guided interventions are still more time-consuming than CT-guided interventions. This is in part due to the longer time needed for MRI sequences compared to CT imaging. Moreover, patient positioning tends to be more challenging in MRI than with CT due to the need for using surface coils. However, it is also due to the relatively low experience with MRI-guided interventions compared to CT guidance, and we expect to see further improvements in the workflow as we gain more experience.

Performed interventions

To date, we have performed 22 procedures using the 0.55T system. These included a variety of diagnostic and therapeutic procedures.

We did five sacroiliac joint injections, including one bilateral. One of those was in a relatively young patient, around 50 years old, where we wanted to avoid radiation. We also treated two very young patients (14 and 16 years old) with periradicular injections. In both, the main reason for MRI guidance was to completely avoid ionizing radiation, especially since the patients are likely to need more imaging in the future.

We performed eight liver biopsies. One was in a patient with a lesion that showed imaging features highly suggestive of hepatocellular carcinoma (HCC), but levels of the alpha-fetoprotein (AFP) tumor marker were normal and CT findings were inconclusive. This necessitated histological clarification. In another case, biopsy was indicated in a patient with liver cirrhosis who had undergone staging solely by MRI. Since no prior CT scan was available, it was uncertain whether the lesion would have been visible using CT. MRI guidance enabled direct targeting without exposing the patient to an additional CT scan for planning purposes. Two patients underwent re-biopsies following inconclusive US-guided liver biopsies that had failed to yield representative samples. Another case involved a very small, suspected metastatic lesion. It was only a few millimeters in size and hardly visible on CT, but clearly visible on MRI. The remaining cases involved suspected metastatic lesions that were more conspicuous on MRI than on CT, justifying the use of MRI guidance.

We also performed one biopsy of a lesion in the rectus abdominis muscle in a 24-year-old woman with suspected desmoid tumor. Another case was a retroperitoneal biopsy in a patient with acute renal failure. Since we couldn't use contrast, MRI was helpful, as we could still see the lesion and surrounding structures like vessels and ureters without any contrast agent.

Two renal biopsies were performed in patients who had previously undergone inconclusive sampling during ureteroscopy.

One MRI-guided wire localization was performed in a very young patient with suspected local recurrence of a previously resected solitary fibrous tumor in the left pelvic region.

Discussion

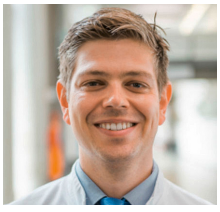
The implementation of our MRI-guided intervention service demonstrates the feasibility of establishing such a program even with a lower field-strength (0.55T) system. The wide bore and potentially reduced artifact burden are advantageous for interventions. The key challenges encountered were primarily related to managing respiratory motion and establishing effective team communication within the unique MRI environment.

Our solutions, including a two-radiologist approach and standardized communication protocols (hand signals, open door), were crucial for success. The evolution of our technical approach, such as adopting finger-pointing for skin marking and using T1 Dixon sequences for combined needle and lesion visualization, reflects practical adaptation to the specific capabilities and limitations of our setup.

Even though the number of procedures performed with MRI guidance in our center is still relatively low, we feel that it is already enough to facilitate a satisfactory learning experience that allows us to perform these interventions with confidence today. Some of the biopsies we performed would have been deemed very challenging or even impossible with CT guidance. Thus, implementing MRI guidance has improved our practice and allows us to offer even more precise diagnostics in cases where histological confirmation is paramount. We believe that our experience can be used as an encouraging example for others who want to establish an MRI-guided intervention unit. Operators with experience in CT- or US-guided interventions will be able to quickly familiarize themselves with MRI guidance and will surely see the benefits in select cases. We have included a number of cases as additional images in figures 2–5.

Conclusion

We successfully established an MRI-guided intervention service using a 0.55T wide-bore scanner. Overcoming the initial challenges of motion and communication required developing specific team strategies and adapting technical workflows. The service effectively addresses the limitations of CT guidance for certain lesions and provides a radiation-free option for selected procedures. Our example shows the possibility to set up a de novo MRI-guided intervention service with relative ease.



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MRI-Guided Versus CT-Guided Interventions: A Focus on the Liver

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Introduction

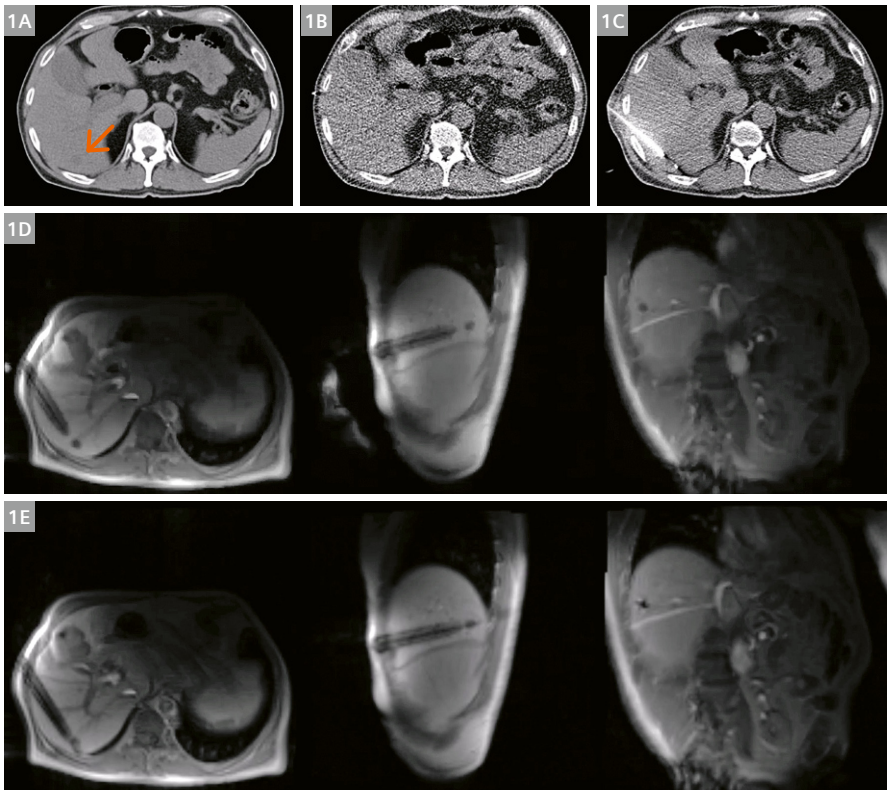
Liver biopsy and thermal ablation of liver tumors are established procedures that are usually performed with computed tomography (CT) or ultrasound (US) guidance. The technical efficacy and safety is generally high. However, small tumors are barely visible (especially on CT imaging), and unfavorable localizations for CT and US guidance (e.g., in the liver dome) increase the risk of sampling errors or incomplete ablation. For liver tumors < 3 cm in size, a sampling error of around 20% has been published [1]. Furthermore, biopsy under CT guidance bears the risk of X-ray exposure, especially for the interventional radiologist.

Advantages of MRI guidance

Magnetic resonance imaging (MRI) provides a high soft tissue contrast that can even be enhanced for a prolonged period with hepatocyte-specific contrast agents. This enables better visualization of liver tumors than with CT or US imaging, where contrast enhancement is limited to a short period of time during the contrast agent administration. Furthermore, the slice orientation can be chosen freely in MRI. This allows a slice orientation along the needle trajectory, displaying needle and target within the slice regardless of the complexity of the angulation. MRI can be performed as fluoroscopic imaging with a fast frame rate of less than one second per image. Even an alternating display of the needle path in perpendicular projections is possible. As a consequence, small lesions and oblique needle access do not represent a limitation for biopsy or ablation under MRI guidance. With regard to liver biopsies, clinical success rates of around 90% for MRI-guided biopsies were described in some early studies, and, in some smaller case series, they were even higher (> 90%) [2]. A direct comparison to CT imaging is currently lacking.

MRI versus CT in liver biopsy

A recently published propensity match analysis from our center has added further evidence [3]. We compared the clinical success (i.e., positive histological sampling) of liver biopsies of small liver lesions (< 2 cm) under MRI versus CT guidance. The MRI data was collected in a prospective study, whereas the CT data was collected from a retrospective cohort. The matching criteria were age, gender, presence of liver cirrhosis, liver lobe, lesion diameter, and skin-to-target distance. After matching, the median lesion diameter was 11.0 mm (MRI) and 12.9 mm (CT). The clinical success rate was 95.8% for MRI versus 73.7% for CT [3]. The in-room time needed for the procedures differed slightly in favor of CT, with a median of 27 minutes versus 39 minutes for MRI. However, we detected a learning curve towards shorter procedure times in MRI. More importantly, we regard the slight time difference as negligible, especially considering the benefit of potentially avoiding a sampling error and the need for repeated procedures. As an important finding, we detected a lower complication rate in the MRI cohort. This is most likely due to the possibility of avoiding vessels in the biopsy path (0% with MRI versus 10.5% with CT, n = 4). All complications were of a minor grade. However, the study cohort size is not large enough to make solid assumptions about this [3]. In order to obtain high-quality evidence for MRI-guided liver biopsy, a prospective randomized study (the MR CORRECT trial) comparing MRI with CT has recently been initiated at LMU Hospital. Patients who are scheduled for a biopsy of a liver lesion < 2 cm and are willing to participate are randomized to either receive an MRI- or CT-guided biopsy (additional use of US in the CT group is allowed). In order to prove the superiority of MRI (assumed clinical success of 97% with MRI versus 79% with CT), 75 patients will be included in each arm. An example of an MRI-guided liver biopsy can be found in Figure 1.



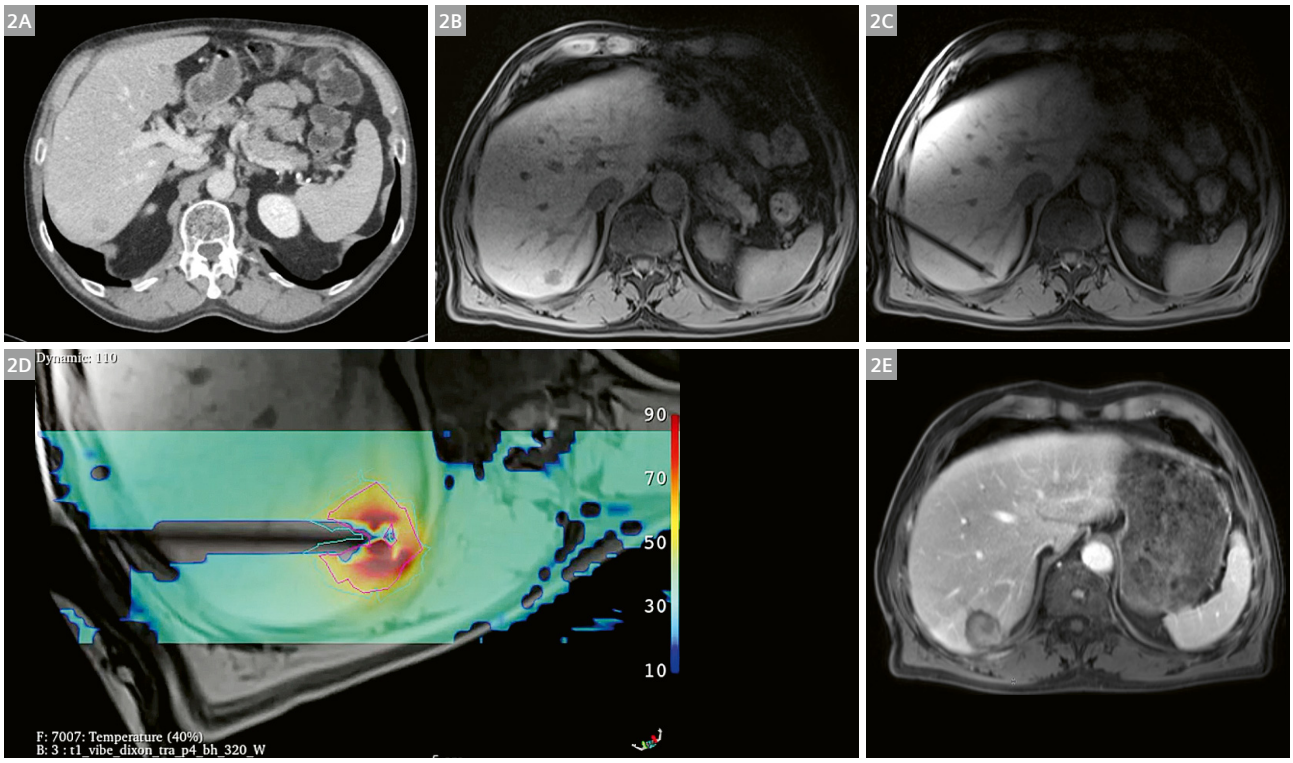
1 Example of a liver biopsy case. Suspicious lesion in Liver Segment 6 in a patient with colorectal cancer. The patient was scheduled for biopsy with CT. **(1A)** shows noncontrast planning CT imaging with an orange arrow marking the lesion, which is barely visible. **(1B)** shows an image during CT fluoroscopy. Due to the low dose during CT fluoroscopy, the lesion is not visible anymore. However, the position of the biopsy needle in **(1C)** looks to be in the position of the target. Unfortunately, the histology was negative and the patient was scheduled for an MRI-guided biopsy. (**1D**, with coaxial needle) and (**1E**, with biopsy gun) show an image slide deck of MR fluoroscopy during the procedure with paraxial, paracoronal, and parasagittal slice orientation (from left to right). The lesion is perfectly visible. The histology was positive with proof of metastatic disease.

Thermal ablation and MR thermometry

The superior image guidance in MRI- versus CT-guided interventions is not restricted to liver biopsy. The advantage of the accuracy of MRI-guided local tumor therapy was demonstrated in a recently published multicenter analysis on the treatment of colorectal liver metastases: A significantly higher local control rate was observed after local thermal ablation under MRI guidance compared to CT guidance (95.4% versus 79.9%). This effect proved to be independent in a multivariate analysis [4]. The mean tumor diameter was 24.7 mm for CT and 27 mm for MRI.

Furthermore, and unlike with CT, methods such as noninvasive real-time temperature measurement can be used in MRI to monitor thermal ablation in order to optimize the effectiveness of the treatment and prevent uncontrolled heating of neighboring sensitive structures (bile duct, large bowel, stomach, etc.). The precision of 3D MR thermometry (using the proton resonance frequency method) versus direct temperature measurement in a gel phantom was shown recently. The median root mean square averaged temperature differences in the voxel near the temperature probe ranged only from 1.4 K to 3.4 K [5].

The microwave antenna and the MR-conditional in-room microwave generator (AveCure, Medwaves GmbH, Gilching, Germany) did not induce relevant artifacts. To date, real-time in vivo applications have been hampered by motion artifacts and radiofrequency (RF) artifacts. As a consequence, one approach was to perform thermometry directly after heating with the generator turned off, or even with the antenna removed. Because of the cooling process in between, the results did not correlate well with the coagulation zone shown in the early follow-up images [6]. Furthermore, this approach does not allow real-time monitoring of the growth of the heating zone, something that would make it possible to adapt the procedure during the ablation (increasing time of ablation if too short, adjusting the needle position, or even prematurely stopping in the case of heating in the direction of heat-vulnerable structures). However, very recently, we demonstrated the robustness of the real-time application of this advanced technology in clinical application during microwave ablation of liver tumors. The volume of thermal dose-predicted lesions and the postprocedural first-day ablation zones

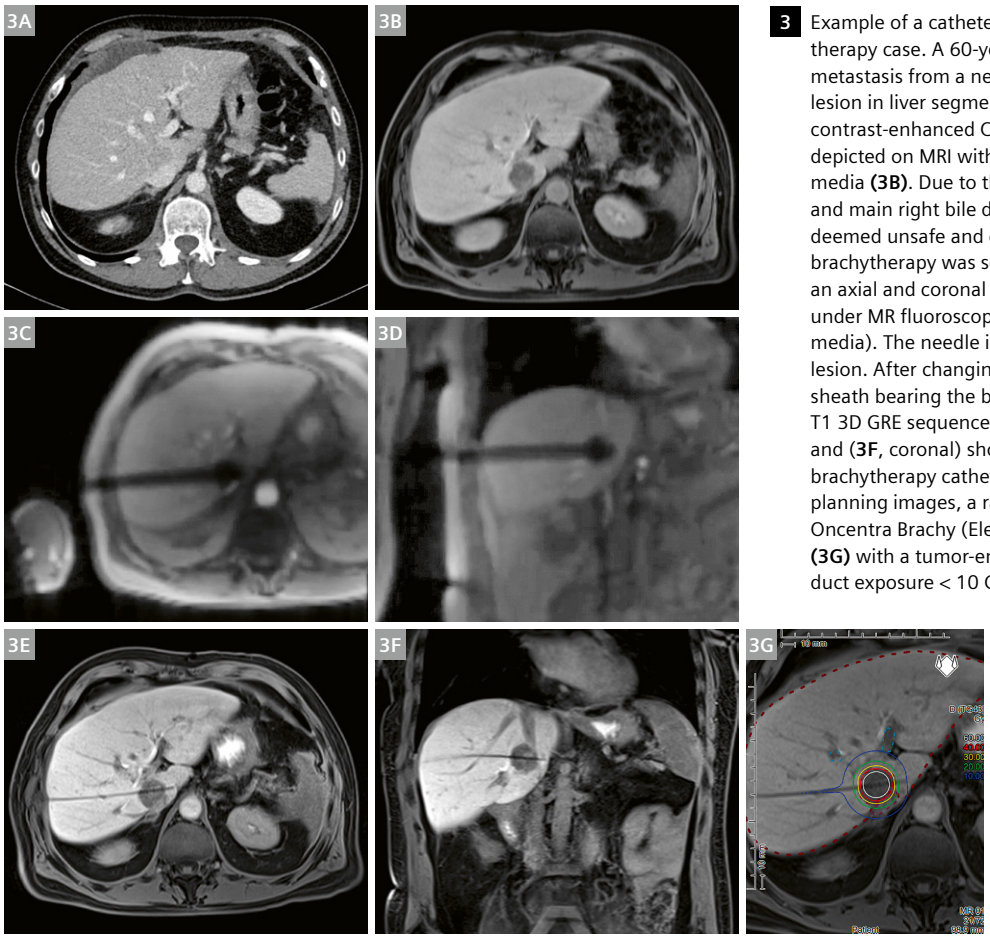


2 Example of an MRI-guided microwave ablation (MWA) case with real-time MR thermometry. An 81-year-old male patient with a single liver metastasis from colorectal cancer. The liver lesion in liver segments 6/7 is faintly visible on contrast-enhanced CT imaging **(2A)**, but is clearly depicted on MRI with hepatocyte-specific contrast media **(2B)**. Under MRI guidance, an MWA needle (ECO Medical Technology Co. Ltd., Nanjing, China) was inserted with a good position in verification imaging (**2C**, T1 3D GRE). Following this, MWA at 120 W for 15 minutes was performed with real-time MR thermometry using Certis software (Pessac, Bordeaux, France) **(2D)**. Contrast-enhanced MRI on postoperative day one **(2E)** showed a coagulation necrosis that perfectly mirrors the predicted heating zone from the MR thermometry.

showed a strong correlation ($R = 0.89$, $p < 0.001$). Figure 2 shows an example image from high-quality MR thermometry using an ECO 100 A microwave ablation (MWA)-generator (ECO Medical Technology Co. Ltd., Nanjing, China). In the analysis, the visual similarity of the proton-resonance thermometry-predicted shape and the ablation-zone shape was graded as perfect in 85.1% of the lesions [7]. However, 6 out of 33 procedures (18.1%) could not be evaluated because of artifacts during the MR thermometry (low signal-to-noise ratio, movement artifacts, susceptibility artifacts due to surgical clips, incomplete coverage). We are about to advance real-time MR thermometry techniques within a research collaboration with the University of Bordeaux in France. In the future, such techniques might make customized local thermal ablation possible. In order to evaluate MRI-guided thermal ablation in more detail, we are running a prospective single cohort trial (the MR MIGHTY trial) with local control rate as the primary endpoint and quality of MR thermometry as one of the secondary endpoints. The aim is to show an improvement of local control rate from 87.7% to 96% [4, 8].

Radiation-based local ablation

In order to also offer local treatment to patients with liver tumors that do not meet optimal treatment criteria for thermal ablation, interventional radiology needs to think beyond heat. Radiation-based local therapies of liver tumors seem like a perfect alternative [9]. Specifically, thermal ablation is restricted if the liver lesion to be treated is larger than 3 cm, is adjacent to central biliary structures, or is localized in the periphery with proximity to heat-sensitive structures (such as the stomach, duodenum, colon, gall bladder, or heart). Since radiation distribution can be predicted much better than heat distribution, and since there is significant tolerability of normal tissue to radiation, radiotherapy presents a valid treatment alternative in these situations. Two forms of radiotherapy can be used: percutaneous radiation or catheter-based radiotherapy/brachytherapy. The distinguishing feature is that catheter-based radiotherapy/brachytherapy offers the possibility of higher single-session dose input with lower-volume exposure for the surrounding tissue [10]. However,



3 Example of a catheter-based radiotherapy/brachytherapy case. A 60-year-old male patient with hepatic metastasis from a neuroendocrine tumor. The liver lesion in liver segments 6/1 is barely visible on contrast-enhanced CT imaging **(3A)**, but is clearly depicted on MRI with hepatocyte-specific contrast media **(3B)**. Due to the proximity to the liver hilum and main right bile duct, a thermal ablation was deemed unsafe and catheter-based radiotherapy/brachytherapy was scheduled. **(3C)** and **(3D)** show an axial and coronal view during needle placement under MR fluoroscopy (with hepatobiliary contrast media). The needle is perfectly in the center of the lesion. After changing the needle to a flexible plastic sheath bearing the brachytherapy catheter, planning T1 3D GRE sequences were acquired. (**3E**, axial) and (**3F**, coronal) show the optimal position of the brachytherapy catheter inside the tumor. Based on the planning images, a radiation plan was calculated using Oncentra Brachy (Elekta AB, Stockholm, Sweden): **(3G)** with a tumor-enclosing dose of 20 Gy, and bile duct exposure < 10 Gy.

the catheter-based method is more invasive and bears the risk of direct complications, such as bleeding. However, the risk for a bleeding complication is low, around 1%, and is especially low in the absence of risk factors like cirrhosis or anticoagulation [11].

Various studies have shown that radiotherapy is just as effective as thermal ablation [12]. Further studies have shown excellent local control rates, even in large tumors [13].

However, as with thermal ablation, the precise application of the catheter is mandatory. In catheter-based radiotherapy/brachytherapy, suboptimal positioning of the catheter(s) can be compensated with an increased ablation zone; however, this increases the exposed volume of nontarget tissue. With low soft tissue contrast on CT imaging, precise placement of the catheters poses a challenge. Application of the catheters under MRI guidance offers the perfect method for precise placement of the catheters (Fig. 3). The good soft tissue contrast in MRI enables optimal targeting of even small tumors [14].
In order to show a more precise delivery of the radiation under MRI guidance, we performed a prospective trial (the MR BRIGHT trial). The data were compared to a historical CT cohort after matching by size, evidence of cirrhosis, and body mass index. The results revealed more precise treatment application under MRI guidance, with significantly less nontarget tissue exposure. The data were presented at the 14th Interventional MRI Symposium in 2024 in Annapolis, MD, USA.

Conclusion

Using MRI guidance for interventions enables higher precision than CT guidance, especially in a soft tissue environment like the liver. It also avoids X-ray exposure. In daily practice, we see improved guidance when using MRI for liver biopsies and local ablations of liver tumors. In order to shape future practice, we are eager to prove this advantage in various trials.

References

1 Stattaus J, Kuehl H, Ladd S, Schroeder T, Antoch G, Baba HA, et al. CT-guided biopsy of small liver lesions: visibility, artifacts, and corresponding diagnostic accuracy. Cardiovasc Intervent Radiol. 2007;30(5):928–35.
2 Fischbach F, Bunke J, Thormann M, Gaffke G, Jungnickel K, Smink J, et al. MR-guided freehand biopsy of liver lesions with fast continuous imaging using a 1.0-T open MRI scanner: experience in 50 patients. Cardiovasc Intervent Radiol. 2011;34(1):188–92.
3 Schmidt VF, Öcal O, Walther V, Fabritius MP, Dietrich O, Kazmierczak PM, et al. Clinical benefits of MRI-guided freehand biopsy of small focal liver lesions in comparison to CT guidance. Eur Radiol. 2024;34(9):5507–5516.
4 Pereira PL, Siemou P, Rempp HJ, Hoffmann R, Hoffmann RT, Kettenbach J, et al. CT versus MR guidance for radiofrequency ablation in patients with colorectal liver metastases: a 10-year follow-up favors MR guidance. Eur Radiol. 2024;34(7):4663–4671.
5 Dietrich O, Lentini S, Ocal O, Bour P, Faller TL, Ozenne V, et al. Accuracy of 3D real-time MRI temperature mapping in gel phantoms during microwave heating. Eur Radiol Exp. 2024;8(1):92.
6 Rempp H, Hoffmann R, Roland J, Buck A, Kickhefel A, Claussen CD, et al. Threshold-based prediction of the coagulation zone in sequential temperature mapping in MR-guided radiofrequency ablation of liver tumours. Eur Radiol. 2012;22(5):1091–100.
7 Ocal O, Dietrich O, Lentini S, Bour P, Faller T, Ozenne V, et al. Predicting liver ablation volumes with real-time MRI thermometry. JHEP Rep. 2024;6(11):101199.
8 Tan W, Deng Q, Lin S, Wang Y, Xu G. Comparison of microwave ablation and radiofrequency ablation for hepatocellular carcinoma: a systematic review and meta-analysis. Int J Hyperthermia. 2019;36(1):264–272.
9 Umutlu MR, Ocal O, Puhr-Westerheide D, Fabritius MP, Wildgruber M, Deniz S, et al. Efficacy and Safety of Local Liver Radioablation in Hepatocellular Carcinoma Lesions within and beyond Limits of Thermal Ablation. Dig Dis. 2024;42(5):461–472.
10 Walter F, Nierer L, Rottler M, Duque AS, Weingandt H, Well J, et al. Comparison of liver exposure in CT-guided high-dose rate (HDR) interstitial brachytherapy versus SBRT in hepatocellular carcinoma. Radiat Oncol. 2021;16(1):86.
11 Mohnike K, Wolf S, Damm R, Seidensticker M, Seidensticker R, Fischbach F, et al. Radioablation of liver malignancies with interstitial high-dose-rate brachytherapy : Complications and risk factors. Strahlenther Onkol. 2016;192(5):288–96.
12 Xi M, Yang Z, Hu L, Fu Y, Hu D, Zhou Z, et al. Radiofrequency Ablation Versus Stereotactic Body Radiotherapy for Recurrent Small Hepatocellular Carcinoma: A Randomized, Open-Label, Controlled Trial. J Clin Oncol. 2025;43(9):1073–1082.
13 Ricke J, Mohnike K, Pech M, Seidensticker M, Ruhl R, Wieners G, et al. Local response and impact on survival after local ablation of liver metastases from colorectal carcinoma by computed tomography-guided high-dose-rate brachytherapy. Int J Radiat Oncol Biol Phys. 2010;78(2):479–85.
14 Ricke J, Thormann M, Ludewig M, Jungnickel K, Grosser O, Wybranski C, et al. MR-guided liver tumor ablation employing open high-field 1.0T MRI for image-guided brachytherapy. Eur Radiol. 2010;20(8):1985–93.

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Urologic Surgery Applications for Interventional MRI

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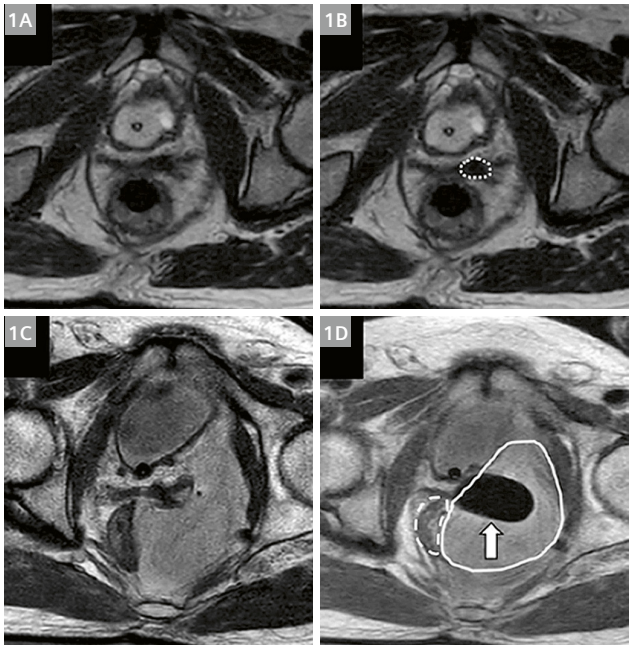
Urologic surgery encompasses and provides care for a full spectrum of disease states including benign and malignant conditions. Furthermore, this specialty serves both children and adults, and both male and female disorders. Radiologic imaging is a critical tool in the diagnosis and management of disease states in these patients. Urologists are one of the highest-volume consumers of imaging for both surgical and nonsurgical specialties. This includes both anatomical and functional applications of imaging. Not only does urology use an imaging-intense suite of diagnostic applications, but it is also fundamentally reliant on imaging as an interventional tool. Whether the imaging is needed for guidance in percutaneous nephrolithotomy, for fluoroscopy-based video urodynamics in urinary dysfunction, for three-dimensional planning and reconstruction prior to complex renal tumor surgery, for diagnosing and managing a lymphatic leak following retroperitoneal surgery, or for planning and executing partial prostate gland cancer ablation – superb imaging is imperative for the best clinical outcome.

The breadth of potential applications for interventional MRI in urologic conditions is expansive and a potential fertile ground for development. On the benign side of the spectrum, possible disease states include pediatric developmental abnormalities such as vesicoureteral reflux, and ureteral duplication and obstruction. Then there is the complex nature of pediatric urologic malignancies. In the men's health realm, there are penile vascular disorders of arteriogenic and venogenic sources; infertility with anatomical and functional abnormalities of the testis, epididymis, and vas deferens; and penile curvature correction with image-guided treatments versus surgical interventions. There is also a multitude of potential interventions for benign prostatic hyperplasia. These include more robust vascular intervention for prostate artery embolization and image-guided delivery of products to the prostate proper. Similarly, in adults, robust near-real-time multiplanar non-fluoroscopic imaging of the kidney and collecting system for renal lithiasis and obstructive processes would be a major step forward. From an oncology perspective, the needs are great. For renal malignancies, planning for partial nephrectomy and tumor enucleation with image guidance based on pre-treatment



1 MR images from saline displacement during MRI-guided cryoablation of a prostate cancer recurrence in the left seminal vesicle bed. **(1A)** Pre-procedural imaging. **(1B)** Pre-procedural imaging showing the location of the lesion (dotted line). **(1C)** Imaging after initial saline displacement. **(1D)** Intra-procedural imaging highlighting approximate area of infused saline (solid line), rectum (dashed line), and ice ball (white arrow). *Reprinted with permission from [1].*

3D reconstruction or more precise tumor ablation would be a tremendous step forward. For urothelial cancer of the bladder, ureter, renal pelvis, or urethra, significant progress could be realized with better staging, surgical planning, and execution. For testicular cancer, image-guided surgical planning and intervention of the orchiectomy and potential retroperitoneal lymph-node dissection, particularly in post-chemotherapy salvage interventions, would optimize this complex surgical procedure. Finally, with respect to prostate cancer, which is the most commonly diagnosed solid tumor in men, the marriage between functional imaging using prostate-specific positron emission tomography (PET) agents, and multi-parametric MRI coupled with 3D ultrasound imaging for diagnosis, staging, and treatment, is unparalleled in oncology.

Coupling the unique attributes of MRI with an interventional environment for the diagnosis, guidance, treatment, and surveillance of urologic conditions has, for the past 15 years, been the focus of a unique collaboration between Interventional Radiology and Urologic Surgery at the Mayo Clinic in Rochester, Minnesota, USA. In 2009, the first interventional cases were conducted to cryo-ablate biopsy-proven prostate cancer recurrences in the seminal vesicles of the prostate. This brought experts from the fields of diagnostic imaging and interventional radiology together with MRI physicists, dedicated MRI technologists, and anesthesiologists to successfully treat patients in a modified diagnostic MRI system. With this collaboration, we were able to successfully engineer modifications to our equipment, ablation techniques, and patient safety routines to innovate and care for patients where previously few options had been available for recurrent prostate cancer. This partnership has yielded tremendous benefits for our patients and has helped them pass significant milestones in their oncologic care pathways, often enabling them to avoid the rigors and side effects of whole-body chemotherapy or androgen deprivation therapy. Landmark developments of techniques in this partnership include: precision transperineal guidance and delivery of the biopsy and treatment device; in-suite/in-bore live ultrasound guidance and confirmation of treatment and biopsy devices; MRI urethral warming and cooling technology; saline pressure hydrodissection techniques and equipment; in-suite/in-bore cystoscopy with delivery and retrieval of ureteral catheters; retrograde pyelography; and the application of multiple ablative technologies (Fig. 1, [1]). These technologies include laser ablation catheters, transrectal- and transurethral-focused ultrasound, radiofrequency ablation, and cryoablation. As a result of the experience gained in the treatment of primary and recurrent prostate cancer, these ablative technologies have been transferred to other organ systems in the interventional MRI space. Application to primary and recurrent cancers of the bladder, vulva, uterus, vagina, ureter, kidney, and penis has been possible, thanks to lessons learned from this initial prostate cancer experience.

In summary, the innovation and application of the unique attributes of the interventional MRI space in urologic disease has been partially realized by the exceptional collaboration of a large team of devoted specialists at the Mayo Clinic. This partnership allows for near-real-time visualization of anatomy during treatment with the prospect of functional feedback and the goal of successfully treating disease with minimal morbidity. We have demonstrated the capacity to develop, test, and use tools, techniques, and unique MRI sequences in daily practice to advance the care of our patients. We believe this is just the beginning of a wonderful journey to view disease and its cure or management in a way that few imagined or have seen before. Exciting prospects for the future include industry partnerships that enable innovations in technology, tools, guidance methods, imaging sequences, equipment, functional real-time feedback to assess physiology, and new ways to deliver drugs, energies, and diagnostic aids [2–4].

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References

1 Lomas DJ, Woodrum DA, McLaren RH, Gorny KR, Felmlee JP, Favazza C, et al. Rectal wall saline displacement for improved margin during MRI-guided cryoablation of primary and recurrent prostate cancer. Abdom Radiol (NY). 2020;45(4):1155-1161.
2 Chrouser K, Kim FJ, Smith A, Stoffel JT, Goldenberg M. Optimizing Outcomes in Urologic Surgery: Intraoperative Environmental, Behavioral, and Performance Considerations. Urol Pract. 2020;7(5):405-412.
3 Gretzer M, Greene K, Chung B, Kobashi K. Identification of Quality Improvement Projects from AUA White Papers. Urol Pract. 2020;7(2):103-108.
4 Smith JA, Howards GM, Preminger GM, Dmochowski RR. Hinman's Atlas of Urologic Sugery. Revised Reprint. Elsevier, 2019.

MRI-Guided Thermal Ablation in Urologic Oncology: The Nijmegen Experience

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Introduction

Interventional magnetic resonance imaging (iMRI) has expanded the possibilities for interventional treatments and is becoming an essential tool for image-guided therapies in urologic oncology [1, 2]. In contrast to ultrasound (US) or computed tomography (CT), MRI provides high-resolution images and excellent soft tissue contrast for prostate and kidney lesions, aiding in precise tumor localization and distinct tumor border identification. This ability supports real-time targeting of lesions while safeguarding adjacent critical structures. Additionally, MRI permits ongoing monitoring and management of the treatment process, including mapping tissue temperatures during thermal therapies. Notably, it does not involve ionizing radiation, which is particularly important for younger patients and for cases requiring several interventions.

Despite their evident advantages, MRI-guided interventions face significant challenges and limitations. Operators and patients must navigate a restricted workspace: Even with the introduction of wide-bore scanners, the bore's size and the need to maintain sterile environments can hinder instrument maneuverability and procedural ergonomics. These spatial issues are compounded by the steep learning curve associated with iMRI techniques. Teams that adopt these methods early on often encounter prolonged procedure times as they refine workflows, improve patient positioning, and gain expertise in rapid sequence acquisition and immediate image interpretation.

Additionally, most MRI-guided procedures require seamless cooperation among radiologists, interventionalists, anesthesiologists, and technologists. This multidisciplinary collaboration is not only crucial for planning images and targeting, but also for addressing real-time challenges and ensuring patient safety. However, it can be logistically complex and resource-intensive. The need for MR-compatible needles, biopsy devices, and monitoring technologies adds another layer of difficulty, as this equipment must be meticulously tested to guarantee image quality and patient safety within highly magnetic environments.

As a result, the financial investment and infrastructure required to establish high-field iMRI systems remain significant. Currently, only a limited number of institutions worldwide have dedicated scanners of 3T or more that are designed for interventional access, along with the necessary sterile-room setup and inventory of devices. These issues – spatial constraints, prolonged setup and imaging durations, the need for multidisciplinary cooperation, specialized tools, and substantial initial costs – can collectively hinder the broader adoption of MRI-guided therapies, even with their clinical potential.

At Radboud University Medical Center (Radboudumc), we have conducted MRI-guided prostate treatments since 2011, with the first MRI-guided kidney treatment following in 2012, utilizing a dedicated wide-bore 3T MRI system (MAGNETOM Skyra, Siemens Healthineers, Erlangen, Germany) within a sterile operating room environment. In this brief communication, we share our insights on the various types of MRI-guided prostate treatments, including cryoablation, focal laser ablation, transurethral ultrasound ablation (TULSA), and MRI-guided cryoablation of renal tumors, which we offer to our patients.

MRI-guided prostate focal therapy

For men diagnosed with localized prostate cancer, active surveillance (AS) and whole-gland treatments like radical prostatectomy (RP) and radiotherapy are widely recognized as standard care options [3]. Nonetheless, these treatments are often associated with considerable side effects, such as urinary incontinence, sexual dysfunction, and bowel issues [4, 5], potentially diminishing the patient's quality of life [5, 6]. Moreover, these options do not consistently provide better cancer control outcomes. Research from the ProTecT trial showed that 15-year cancer-specific survival rates for both RP and external beam radiotherapy in patients with low- to intermediate-risk prostate cancer were similar to those achieved with AS alone [7]. However, AS was linked to increased rates of disease progression and metastasis. To improve the balance between treatment efficacy and associated risks, newer image-guided strategies like high-intensity focused ultrasound (HIFU), cryoablation, focal laser ablation (FLA), and

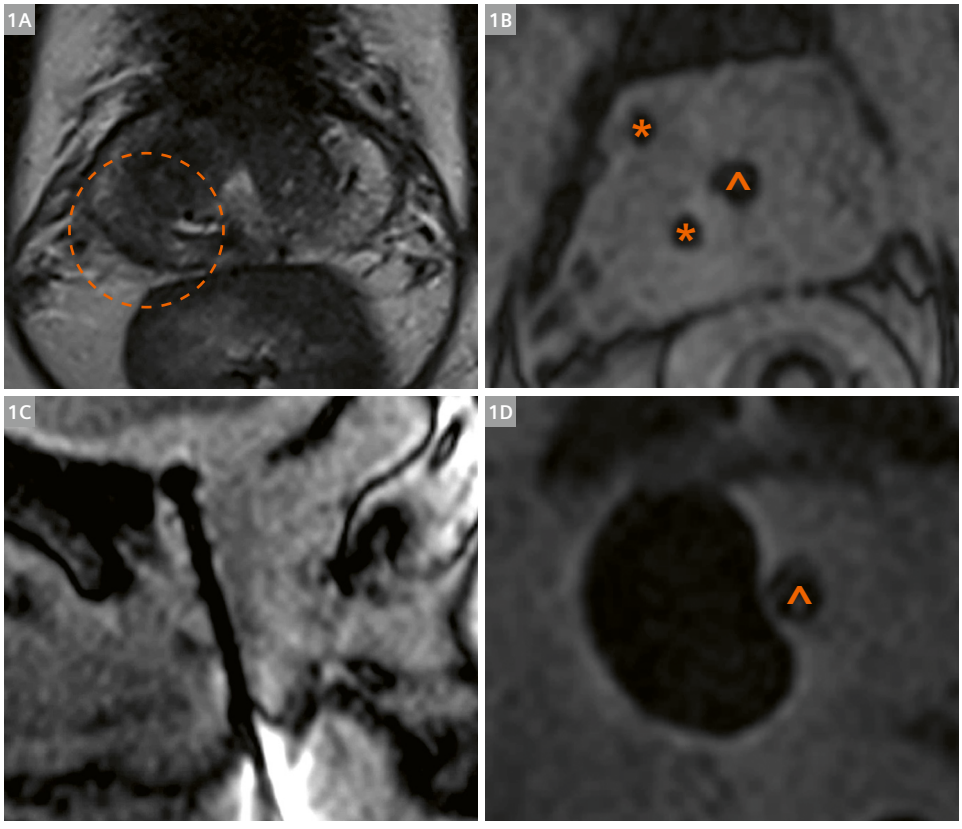
transurethral ultrasound ablation (TULSA) have been developed. These techniques aim to minimize side effects while still providing effective cancer management. At Radboudumc, we have experience in performing MRI-guided cryoablation, FLA, and TULSA in prostate cancer patients. For each treatment type, we will provide a brief overview.

Cryoablation

Cryoablation, also known as cryotherapy, is a minimally invasive thermal procedure designed to address localized recurrent prostate cancer. This method causes irreversible cell damage by freezing the tumor tissue and can be conducted as either whole-gland ablation or partial ablation, based on the size and location of the tumor, as well as the patient's overall health condition.

Cryoablation can be performed under transrectal-ultrasound (TRUS), CT or MRI guidance. When compared to TRUS and CT guidance, MRI guidance offers advantages in providing accurate prostate cancer localization; in targeting the lesion, especially anterior and apical lesions; in monitoring the freezing process in (near) real time without acoustic shadowing of the ice ball [8]; and in avoiding ionizing radiation.

Previously, we published our initial experience and one-year follow-up results after MRI-guided focal cryoablation in patients with a local recurrence [9, 10]. All of our patients underwent treatment under general anesthesia and were placed in a lithotomy position on the MR table. All procedures were performed in a closed-bore MRI system (1.5T MAGNETOM Avanto, Siemens Healthineers, Erlangen, Germany) or in a wide-bore 3T system (MAGNETOM Skyra). The legs are placed in a dedicated leg holder to gain access to the perineum. A urethral warmer and a rectal warmer are inserted and continuously flushed with warm saline to prevent both structures from freezing. T2-weighted images are acquired to relocalize the tumor (Fig. 1A). Cryoneedles (Galil Medical Ltd., Yoqneam, Israel) are transperineally inserted in the tumor by an interventional radiologist using real-time balanced steady-state free precession sequences (TrueFISP) or near-real-time T1-weighted volumetric interpolated gradient-echo MR images (T1-VIBE) (Figs. 1B, 1C). To get an accurate impression of the needle position, MR images were directly shown on an in-room monitor in at least two orientations. The number and type of cryoneedles used depended on the size and location of the treatment area. In general, two freeze-thaw cycles were performed: One cycle consisted of 10 minutes active freezing, 2 minutes of passive thawing, and 1 minute of active thawing. During these cycles, near-real-time T1-VIBE series were acquired to monitor ice-ball growth and adjacent critical structures (Fig. 1D). After the procedure, the urethral warmer was changed for a urethral catheter. Patients were discharged the day after the procedure.



1 A 73-year-old male patient with local prostate cancer recurrence in the right peripheral zone after previous radiotherapy. **(1A)** Axial T2-weighted image of the prostate with the local recurrence in the orange circle. **(1B)** Axial T1-VIBE of the prostate with two needles (*) and a urethral warmer (^) in situ. **(1C)** Sagittal T1-VIBE with a cryoneedle in situ. **(1D)** Axial T1-VIBE at the end of the first freezing cycle with the ice ball represented by the large black signal void, and the urethral warmer (^).

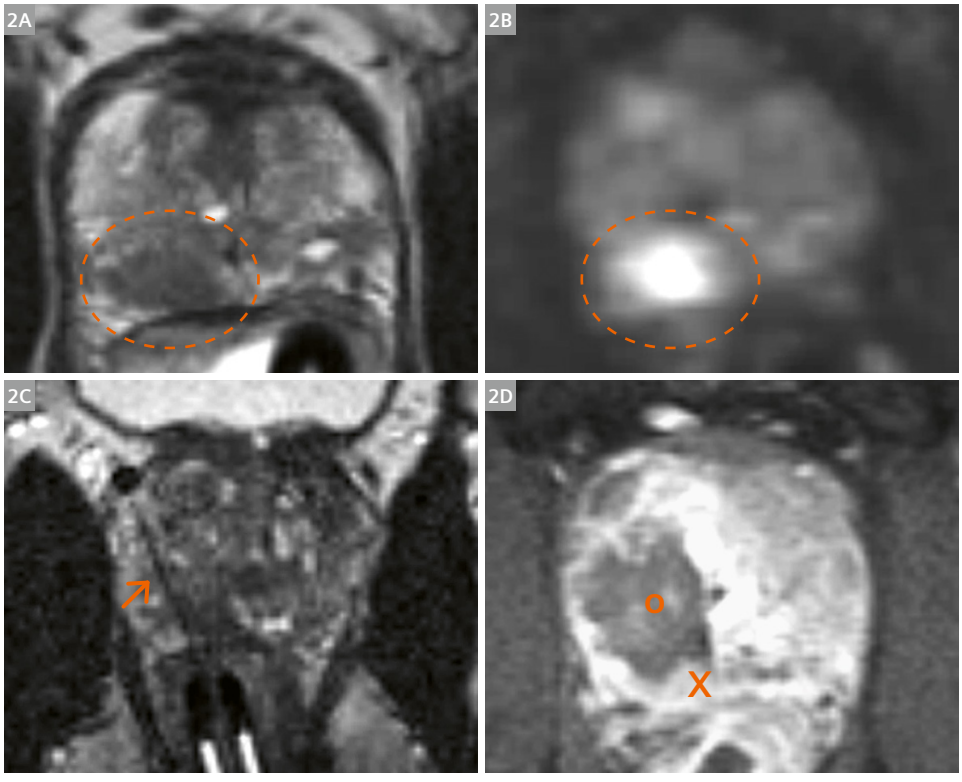
More recently, we have described the 10-year follow-up results of 114 patients that were treated with MRI-guided focal cryoablation in a salvage setting, i.e., patients with a local prostate cancer recurrence after previous radiotherapy or radical prostatectomy [11]. These data demonstrated that MRI-guided salvage focal cryoablation is an effective and safe treatment option in both patient groups, but that patients with a previous radical prostatectomy had more complications, an increased risk of recurrence, and a shortened time to additional treatment than patients with a local recurrence after radiotherapy (RT).

Focal laser ablation

FLA, also referred to as laser-induced interstitial thermal therapy (LITT), involves the targeted delivery of laser energy to tumor tissue via a laser fiber inserted transrectally or transperineally under image guidance – typically using TRUS or MRI. Once the fiber is accurately positioned within the tumor, laser energy is emitted through the fiber, generating localized heat. When the temperature exceeds 60°C, irreversible thermal damage occurs, resulting in targeted tissue ablation.

This technique is relatively rapid and produces a well-defined ablation zone. It is considered minimally invasive, as it can be performed under local anesthesia or light sedation. Key advantages of FLA include the absence of imaging artifacts from the laser fiber, which allows for precise tumor visualization and targeting, and the ability for real-time temperature mapping during MRI-guided procedures [12]. This enables accurate intra-procedural monitoring and control of the ablation process – an advantage not achievable with TRUS guidance.

At our institution, we offer MRI-guided focal laser ablation under local anesthesia in an outpatient setting. Local anesthesia (i.e., periprostatic block) is administered by bilateral injections of bupivacaine under TRUS guidance. Patients are treated transrectally or transperineally, depending on the size and location of the tumor. Relocalization of the tumor is achieved with T2-weighted or diffusion-weighted imaging (DWI) (Figs. 2A, 2B), and the lesion is targeted with a coaxial needle using TrueFISP imaging in at least two directions. The laser fiber is inserted through the coaxial needle and the position of the fiber tip is verified with TrueFISP images (Fig. 2C). During the ablation process, temperature monitoring is continuously performed in real time and visualized with dedicated thermometry software on a stand-alone PC. Based on the size of the lesion, multiple ablations per lesion may be necessary. The laser fiber is relocated, and the ablation process is repeated. T1-weighted contrast-enhanced images are instantly acquired to assess the ablation zone (Fig. 2D). In cases of incomplete tumor coverage, one or more re-ablations are performed in the same session.



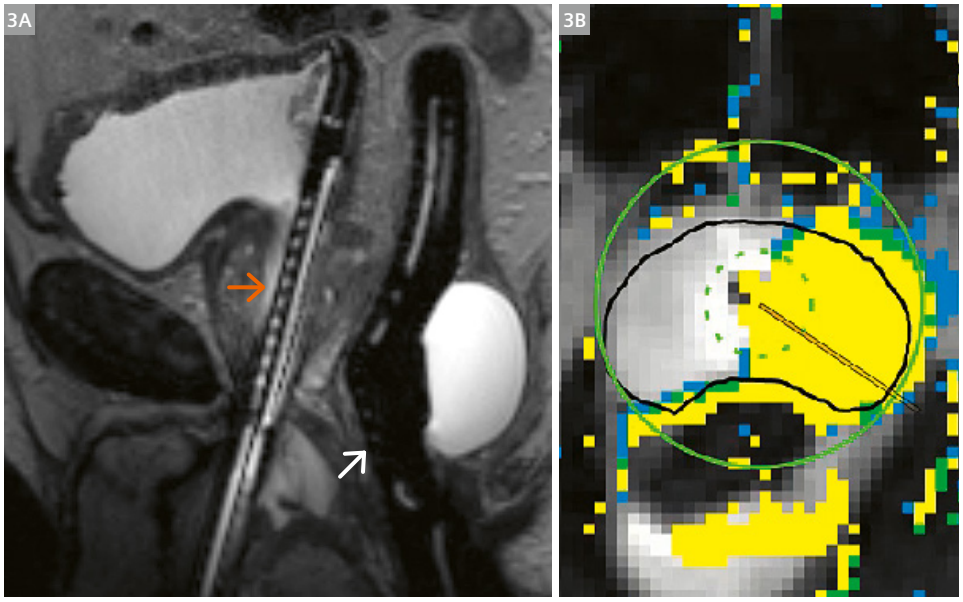
2 A 64-year-old male patient with ISUP 2 prostate cancer (Gleason Score 3 + 4 = 7) in the right peripheral zone, which was treated with MRI-guided focal laser ablation. **(2A, 2B)** Axial T2W image (2A) and calculated b = 1400 s/mm² DWI (2B) of the prostate with the tumor in the orange ellipse. **(2C)** Axial TrueFISP with the laser fiber in situ marked by the orange arrow. **(2D)** Axial T1W contrast-enhanced image after seven ablations. The black signal void (o) represents the ablation zone. Because of inadequate coverage (X) near the rectal wall, another ablation was performed at that site.

Conventionally, separate systems have been employed for laser energy management and temperature monitoring software. Recently, we shared the initial outcomes of a novel integrated laser ablation system that combines laser energy control with real-time MR thermometry [13]. This unified system enhances safety by automatically halting laser energy once a predetermined temperature threshold is surpassed at a specific location. By positioning this point near critical structures, we can prevent unintentional thermal injuries. We treated 10 patients using this system, with all procedures being technically successful. Each patient underwent three to seven ablations, and we achieved a median tumor coverage of 100% (interquartile range: 95%–100%). After a year, 8 out of 12 patients experienced local tumor progression-free survival.

Transurethral ultrasound ablation

TULSA is a relatively new, minimally invasive treatment option for prostate cancer and benign prostatic hyperplasia (BPH). During TULSA, prostatic (tumor) tissue is heated and destroyed by high-intensity ultrasound energy supplied by a dedicated ultrasound device (TULSA-PRO, Profound Medical Corp., Mississauga, Canada) inserted in the prostatic urethra. It is an incision-free technique performed under general anesthesia. Furthermore, it can be used for whole-gland treatment as well as for focal treatment. MRI is fully embedded in the TULSA technique, since it is used to guide, plan, and monitor the ablation in real time.

Patients are treated in a supine position under general anesthesia. A rigid ultrasound applicator is inserted into the prostatic urethra and attached to an MR-compatible robotic arm situated between the patient's legs on the MR table. This ultrasound applicator comprises 10 independent transducer elements that can each emit directional ultrasound energy. A rectal cooling device is placed in the rectum to prevent heat damage. The location of the urethral device is verified using high-resolution sagittal 3D T2-weighted images (Fig. 3A). The treating physician (interventional radiologist/urologist) delineates the treatment area using axial T2-weighted images with a slice thickness of 3 mm. Ablation is monitored in real-time through an echo-planar (EPI) MR thermometry sequence with a temporal resolution of 6 seconds across 12 slices (Fig. 3B). Using the information from these images, the optimal acoustic power and frequency for each transducer element are calculated and automatically implemented, including the rotation rate of the ultrasound applicator. This feedback system allows for high treatment precision, which is a key feature of TULSA treatment. Following the ablation, T1-weighted contrast-enhanced images are obtained to evaluate the ablation zone.



3 A 76-year-old male patient with ISUP 2 prostate cancer (Gleason Score 3 + 4 = 7) in the left peripheral zone was treated with a hemiablation of the left part of the prostate using TULSA. **(3A)** Sagittal 3D T2-weighted image with the urethral device (TULSA-PRO, Profound Medical Corp., Mississauga, Canada, orange arrow) and rectal cooling device (white arrow) in situ. **(3B)** Axial EPI MR thermometry image with a visualization of the thermal dose as overlay. The prostate is delineated by the black line.

MRI-guided renal cryoablation

The management of early-stage renal tumors has evolved significantly with the advent of minimally invasive ablative techniques [14, 15]. Among these, cryoablation has been established as a safe and effective nephron-sparing alternative to partial nephrectomy in small renal tumors, offering the benefits of reduced morbidity, shorter hospital stays, and preservation of renal function, particularly in patients with comorbidities or limited renal reserve [16].

In recent years, multiple studies have shown excellent and durable results in terms of overall survival and local control for percutaneous cryoablation of small renal tumors [17, 18]. Renal cryoablation is traditionally performed under ultrasound or CT guidance to allow lesion localization and probe targeting. Importantly, the success of cryoablation is highly dependent on accurate tumor localization, precise probe placement, and visualization of the ablation zone, allowing appropriate ablation margins [19, 20]. Several studies have recently demonstrated the feasibility and efficacy of MRI-guided cryoablation for renal tumors [21, 22]. Compared to US or CT guidance, MRI provides superior soft tissue contrast, volumetric imaging, and multiplanar capabilities, making it especially advantageous for guiding and assessing cryoablation procedures. In addition, MRI can directly visualize the evolving ice ball and surrounding tissue interfaces with high resolution, enabling real-time procedural control and improved treatment precision [23].

Here we present our workflow for MRI-guided cryoablation of small renal tumors and highlight the specific benefits of interventional MRI using two example clinical cases.

Target tumor visualization

A key first step in image-guided ablation is to re-identify and re-assess the target tumor and potentially adjust the treatment plan. Accurate visualization of the target tumor location and extent is essential. MRI inherently excels in soft tissue contrast, allowing precise tumor localization and delineation without the need for contrast administration (Case 1A, Case 2B). In the setting of renal cryoablation, patients often have compromised kidney function, due to issues such as chronic kidney disease or prior tumor nephrectomy, which places restrictions on contrast administration. More importantly, lesion localization for centrally located, non-exophytic tumors can be particularly challenging using CT guidance without contrast agents. MRI offers the ability to repeatedly image the target tumor and relevant anatomy using native sequences, allowing high accuracy in target tumor determination and verification of probe positioning. Finally, procedures can be performed fully radiation-free, which can be an important advantage for specific patient groups in which use of ionizing radiation should be limited or avoided.

Real-time needle targeting

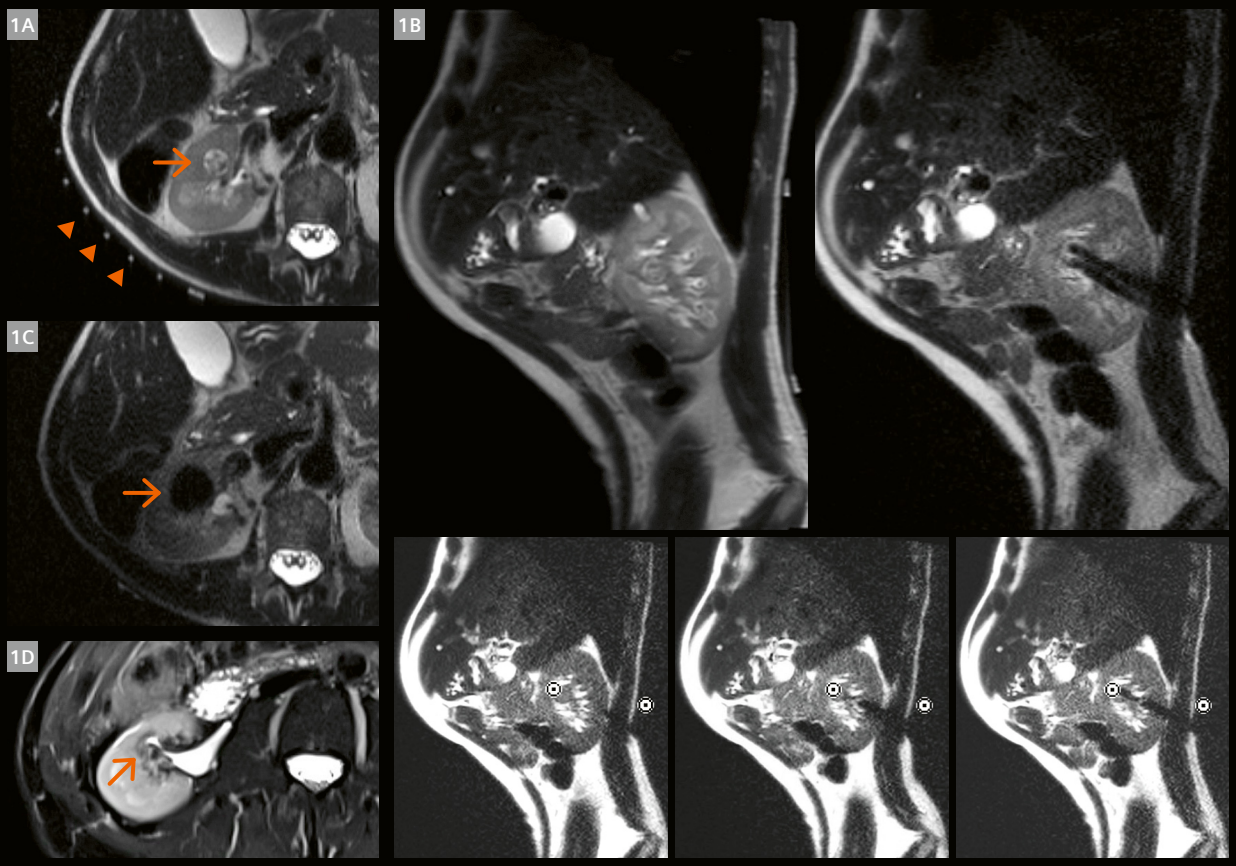
A second benefit of MRI lies in its ability to offer real-time, multiplanar imaging planes along each desired imaging orientation. Although traditional image guidance with US or CT allows adequate renal tumor targeting, CT targeting can be particularly challenging in centrally located lesions, which are often inconspicuous on native CT imaging. Contrast-enhanced imaging allows improved tumor visualization, but can only be used with limitations and does not allow repeated tumor visualization, e.g., to verify accurate cryoprobe placement with respect to the target tumor. Similarly, US allows two-dimensional real-time imaging of target lesions and probe guidance, but lesion conspicuity can vary substantially. Three-dimensional orientation, particularly in multi-probe cases, can be challenging and can limit optimal cryoprobe positioning. With precise needle trajectory planning and subsequent alignment of real-time TrueFISP or HASTE MR imaging planes, it is possible to achieve direct guidance for the placement of multiple cryoprobes (Case 1B). Nevertheless, patient access within the scanner bore is limited and the in-bore MRI-guided targeting workflow still requires specific expertise to be successful. Additionally, needle artifacts may cause challenges in verifying the exact probe position and in distinguishing multiple needles that are located close together. After each real-time MRI-positioned needle, a multi-slice T2-weighted HASTE sequence is performed to assess final needle position and confirm accurate lesion targeting.

Dynamic monitoring of ice-ball progression

Another crucial, and arguably the most beneficial, capability of MRI in guiding cryoablation procedures is its inherent ability to monitor cryoablation zone evolution with high precision, three-dimensionally and dynamically. Due to the freezing of water molecules, the MRI signal is drastically reduced for frozen tissue, leading to a sharply demarcated signal void corresponding to the ice ball extent in all conventional MRI sequences. In contrast, US is limited by two-dimensional assessment and acoustic shadowing, while CT is limited by low-contrast resolution between frozen and non-frozen tissue, complicating the accurate

Case 1: Papillary renal cell carcinoma in the right kidney

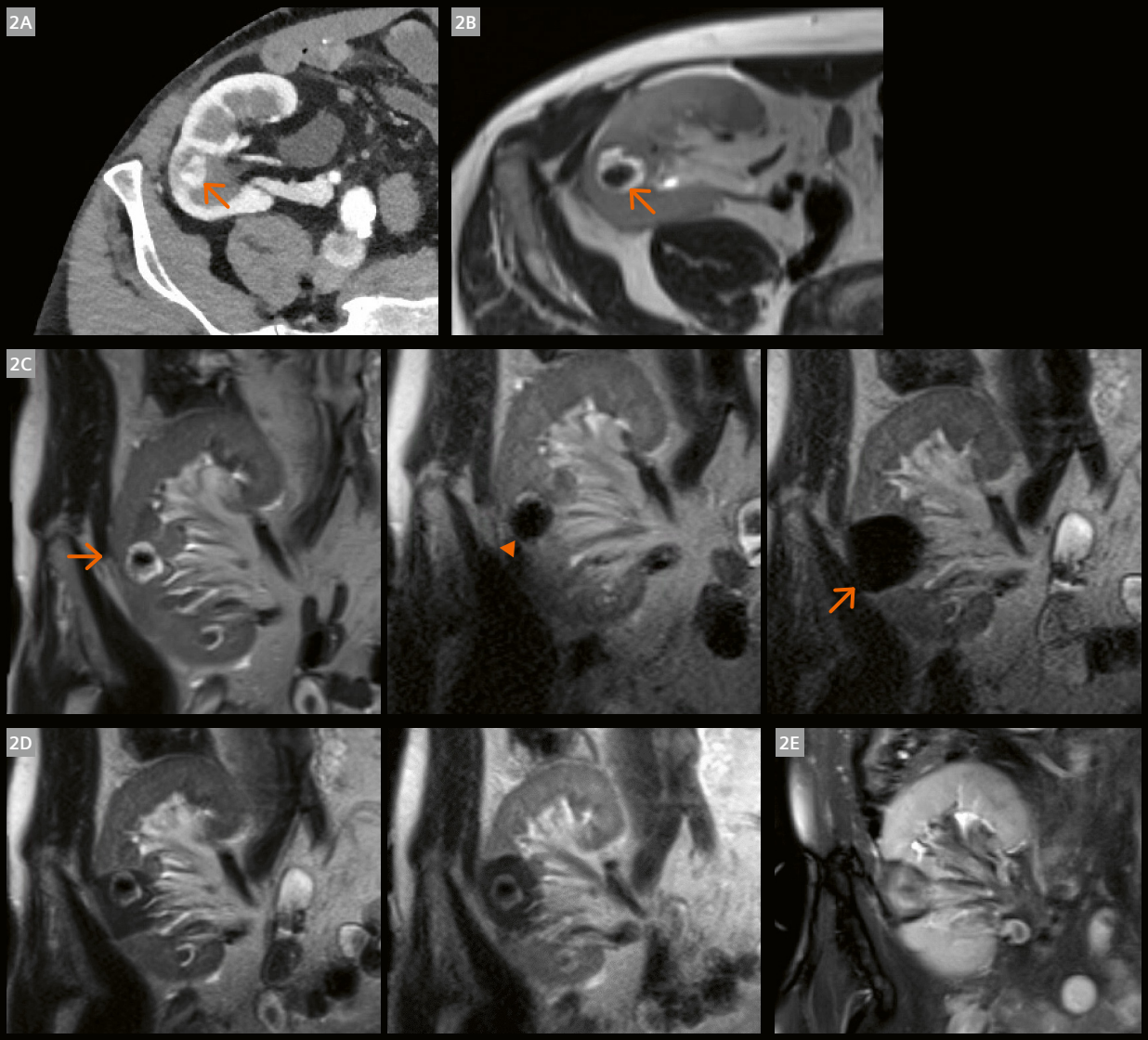
A 66-year-old male patient was diagnosed with a 2 cm tumor in the right kidney, detected as an incidental finding on routine abdominal imaging. Subsequent biopsy showed a papillary renal cell carcinoma (RCC) with a clinical stage of T1a. The multidisciplinary tumor board chose percutaneous cryoablation as the preferred treatment, and the patient was referred to the interventional radiology clinic for MRI-guided cryoablation.



1 **(1A)** Intra-procedural pre-treatment T2-weighted HASTE at the start of the procedure depicts the 2 cm target lesion, centrally located in the right kidney (orange arrow). The patient is in prone position, and an MR-visible silicone line grid (made in-house) is placed on the patient's back to facilitate entry-point localization (orange arrowheads). Imaging is acquired in controlled apnea to mitigate target motion. **(1B)** Sagittal T2-weighted HASTE (top left) oriented through the planned needle trajectory using a dedicated interactive software tool for support during needle-guided procedures. The images show the target lesion location and enable visualization of feasible entry point. After localizing the skin entry point, the cryoprobe is inserted 3–5 cm into the subcutaneous tissue outside the scanner bore. Thereafter, sagittal interactive, realt-time HASTE imaging (bottom row) with planned target and entry points overlaid allows direct image guidance and precise needle advancement to the target position within the scanner bore. A second sagittal T2-weighted HASTE (top right) shows the final needle position of two sequentially inserted cryoprobes. **(1C)** Intraprocedural post-treatment T2-weighted HASTE at the end of the second freezing cycle shows the final cryoablation zone encompassing the target lesion. **(1D)** Twelve-month follow-up MRI shows involution of the ablation zone without evidence of local recurrence.

Case 2: Clear cell renal cell carcinoma in a transplant kidney

A 68-year-old male patient was diagnosed with a 1.5 cm hypervascular lesion in a transplant kidney located in the right iliac fossa on abdominal CT imaging. Subsequent biopsy showed clear cell RCC. The patient had previously undergone a kidney transplant due to chronic kidney disease and renal insufficiency. To maximally preserve kidney function, percutaneous cryoablation was chosen as the preferred treatment and the patient was referred to the interventional radiology clinic for MRI-guided cryoablation.



2 **(2A)** Diagnostic CT imaging shows a 1.5 cm hypervascular lesion (orange arrow) in the transplant kidney located in the right iliac fossa. **(2B)** Intra-procedural pre-treatment T2-weighted HASTE at the start of the procedure allows re-identification of the target lesion (orange arrow) and clear depiction of lesion extent. **(2C)** Coronal T2-weighted HASTE (left) shows the target lesion (orange arrow) before needle insertion; the needle locations (middle) after insertion of two cryoprobes (arrowhead), indicated by the needle artefact signal voids within the target lesion; and the final cryoablation zone (right) at the end of the second freeze cycle (orange arrow). **(2D)** Rigid image co-registration and overlay of the intraprocedural pre- and post-treatment MRI (left) shows ice-ball coverage in relation to the target tumor, illustrating a narrow cryoablation margin at the superior tumor boundary. After cryoprobe re-positioning, a third freeze cycle was applied. Image overlay after the third freezing cycle now confirms adequate tumor coverage with clear margins along the tumor boundary. **(2E)** Three-month post-ablation MRI confirms adequate coverage of the target tumor by the treatment zone without evidence of recurrence or residual enhancement.

three-dimensional monitoring of the extent of the ice ball. In our practice, we dynamically monitor ice-ball progression with a multi-slice T2 HASTE sequence covering the treatment region and providing a volumetric assessment of ice-ball coverage approximately every 45 seconds (Case 1C, Case 2C). Consequently, cryoprobe settings can be adjusted to ensure optimal tumor coverage while maintaining safe distances to surrounding critical structures. In cases where critical structures such as hollow viscera or the pancreas are nearby, performing an additional hydrodissection can be considered to increase the distance between the target tumor and these critical structures. This capability is therefore not only crucial to achieve adequate tumor coverage but also to avoid complications.

Intra-procedural outcome assessment

Finally, an important clinical benefit of MRI's ability to accurately depict both the target tumor and the cryoablation zone is that it enables intraprocedural assessment of ablation completeness. Although achieving sufficient ablation margins is widely recognized as a crucial determinant of local control following thermal ablation in various cancer types, appropriate strategies that allow accurate assessment of tumor coverage during the intervention itself are still lacking. In our workflow, standardized pre- and post-ablation imaging using T2-weighted HASTE imaging in apnea is performed at the beginning of the procedure and at the end of the final freezing cycle. By performing rigid MR-MR co-registration of these pre- and post-ablation imaging volumes, a three-dimensional overlay view of the ice ball with respect to the target tumor can be obtained (Case 2D), allowing improved assessment of tumor coverage and margin extent. In cases of suspected insufficient margins, immediate corrective treatment can be performed by repositioning the probe and performing an additional cryoablation cycle to obtain an adequate ablation result (Case 2D). This approach is therefore crucial to ensure local control (Case 1D, Case 2E) and optimize outcomes of MRI-guided cryoablation.

Outlook and perspectives

The recent advancements and increasing applications of interventional MRI, particularly using wide-bore 3T systems, have highlighted the clinical potential of MRI-guided procedures in urologic oncology. With growing evidence supporting the safety, efficacy, and precision of MRI-guided interventions for prostate and kidney tumors, the field is poised to enter a new era of minimally invasive, organ-preserving treatments. To make MRI-guided interventions mainstream, several structural and technical prerequisites must be addressed: access to dedicated interventional MRI suites, streamlined workflows, integrated MR-compatible equipment, and training programs for multidisciplinary teams. As seen in the Radboudumc experience, consistent procedural success demands not only technological infrastructure but also substantial institutional investment in expertise, planning, and collaboration.

For prostate cancer, MRI-guided focal therapies such as cryoablation, FLA, and TULSA offer effective alternatives to whole-gland treatment, reducing morbidity while maintaining oncologic control. The prospective, multicenter randomized controlled ENFORCE trial (NCT06223295), which is being coordinated by our center and is currently enrolling, aims to demonstrate non-inferior oncologic efficacy and superior quality of life from focal therapy versus standard-of-care radical prostatectomy or radiation therapy in localized intermediate-risk prostate cancer. The study has the potential to significantly alter the current treatment landscape. Similarly, MRI-guided renal cryoablation enables safe and precise treatment of small renal masses, especially in challenging anatomical locations or in patients unsuitable for surgery. The ability to perform dynamic monitoring, intra-procedural margin assessment, and radiation-free guidance is shifting the paradigm from reactive to truly precision-targeted, adaptive therapies. As integrated MR thermometry and treatment planning software continue to evolve, these capabilities will be further enhanced, expanding the role of iMRI beyond niche indications.

To fully realize this potential, efforts must focus on scalability, standardization, and broader clinical validation. Future directions include developing compact and lower-cost MRI systems tailored for interventions, incorporating artificial intelligence for real-time image interpretation and needle tracking, and validating protocols through multicenter trials such as ENFORCE. Given that in-bore MRI-guided biopsy is well-established for prostate cancer, extending its application to renal biopsies – particularly in patients with high-risk or complex renal lesions – could likewise prove to be transformative. As MRI-guided procedures become increasingly automated, safer, and more efficient, they are expected to transition from specialized academic environments into broader clinical practice, ushering in a new standard for precision urologic care.

References

1 Ghai S, Ni TT, Pavlovich CP, Futterer JJ, Schade GR, Sanchez-Salas R, et al. New kids on the block: MRI guided transrectal focused US, TULSA, focal laser ablation, histotripsy - a comprehensive review. Prostate Cancer Prostatic Dis. 2025. Epub ahead of print.

2 Bomers JG, Sedelaar JP, Barentsz JO, Fütterer JJ. MRI-guided interventions for the treatment of prostate cancer. AJR Am J Roentgenol. 2012;199(4):714–20.

3 Cornford P, van den Bergh RCN, Briers E, Van den Broeck T, Brunckhorst O, Darraugh J, et al. EAU-EANM-ESTRO-ESUR-ISUP-SIOG Guidelines on Prostate Cancer-2024 Update. Part I: Screening, Diagnosis, and Local Treatment with Curative Intent. Eur Urol. 2024;86(2):148–163.

4 Donovan JL, Hamdy FC, Lane JA, Young GJ, Metcalfe C, Walsh EI, et al. Patient-Reported Outcomes 12 Years after Localized Prostate Cancer Treatment. NEJM Evid. 2023;2(4):EVIDoa2300018. Erratum in: NEJM Evid. 2023;2(6):EVIDx2300122.

5 Wilt TJ, Jones KM, Barry MJ, Andriole GL, Culkin D, Wheeler T, et al. Follow-up of Prostatectomy versus Observation for Early Prostate Cancer. N Engl J Med. 2017;377(2):132–142.

6 Kord E, Jung N, Posielski N, Jiang J, Elsamanoudi S, Chesnut GT, et al. Prospective Long-term Health-related Quality of Life Outcomes After Surgery, Radiotherapy, or Active Surveillance for Localized Prostate Cancer. Eur Urol Open Sci. 2022;48:60–69.

7 Hamdy FC, Donovan JL, Lane JA, Metcalfe C, Davis M, Turner EL, et al. Fifteen-Year Outcomes after Monitoring, Surgery, or Radiotherapy for Prostate Cancer. N Engl J Med. 2023;388(17):1547–1558.

8 Overduin CG, Jenniskens SFM, Sedelaar JPM, Bomers JGR, Fütterer JJ. Percutaneous MR-guided focal cryoablation for recurrent prostate cancer following radiation therapy: retrospective analysis of iceball margins and outcomes. Eur Radiol. 2017;27(11):4828–4836.

9 Bomers JG, Yakar D, Overduin CG, Sedelaar JP, Vergunst H, Barentsz JO, et al. MR imaging-guided focal cryoablation in patients with recurrent prostate cancer. Radiology. 2013;268(2):451–60.

10 Bomers JGR, Overduin CG, Jenniskens SFM, Cornel EB, van Lin ENJT, Sedelaar JPM, et al. Focal Salvage MR Imaging-Guided Cryoablation for Localized Prostate Cancer Recurrence after Radiotherapy: 12-Month Follow-up. J Vasc Interv Radiol. 2020;31(1):35–41.

11 Wimper Y, Overduin CG, Sedelaar JPM, Veltman J, Jenniskens SFM, Bomers JGR, et al. MRI-Guided Salvage Focal Cryoablation: A 10-Year Single-Center Experience in 114 Patients with Localized Recurrent Prostate Cancer. Cancers (Basel). 2023;15(16):4093.

12 Odéen H, Parker DL. Magnetic resonance thermometry and its biological applications - Physical principles and practical considerations. Prog Nucl Magn Reson Spectrosc. 2019;110:34–61.

13 Wimper Y, Te Molder LPW, Sedelaar JPM, Bomers JGR, Overduin CG, Fütterer JJ. MR-Guided Transrectal Focal Laser Ablation for Localized Low- and Intermediate-Risk Prostate Cancer: Initial Outcomes Using an Integrated Laser Ablation System. J Vasc Interv Radiol. 2025;36(5):795–804.

14 Mouraviev V, Joniau S, Van Poppel H, Polascik TJ. Current status of minimally invasive ablative techniques in the treatment of small renal tumours. Eur Urol. 2007;51(2):328–36.

15 Dong L, Liang WY, Ya L, Yang L, Qiang W. A Systematic Review and Meta-Analysis of Minimally Invasive Partial Nephrectomy Versus Focal Therapy for Small Renal Masses. Front Oncol. 2022;12:732714.

16 Zondervan PJ, Buijs M, de la Rosette JJ, van Delden O, van Lienden K, Laguna MP. Cryoablation of small kidney tumors. Int J Surg. 2016;36(Pt C):533–540.

17 Breen DJ, King AJ, Patel N, Lockyer R, Hayes M. Image-guided Cryoablation for Sporadic Renal Cell Carcinoma: Three- and 5-year Outcomes in 220 Patients with Biopsy-proven Renal Cell Carcinoma. Radiology. 2018;289(2):554–561.

18 Spiliopoulos S, Marzoug A, Ra H, Arcot Ragupathy SK. Long-term outcomes of CT-guided percutaneous cryoablation of T1a and T1b renal cell carcinoma. Diagn Interv Radiol. 2021;27(4):524–528.

19 de Jager NS, van Oostenbrugge TJ, Pätz T, Jenniskens SFM, Fütterer JJ, Langenhuijsen JF, et al. Intraoperative MRI-derived volumetric ablation margins and initial correlation with local outcome after MRI-guided cryoablation of renal tumors. Cancer Imaging. 2023;23(1):31.

20 Georgiades C, Rodriguez R, Azene E, Weiss C, Chaux A, Gonzalez-Roibon N, et al. Determination of the nonlethal margin inside the visible "ice-ball" during percutaneous cryoablation of renal tissue. Cardiovasc Intervent Radiol. 2013;36(3):783–90.

21 van Oostenbrugge TJ, Langenhuijsen JF, Overduin CG, Jenniskens SF, Mulders PFA, Fütterer JJ. Percutaneous MR Imaging-Guided Cryoablation of Small Renal Masses in a 3-T Closed-Bore MR Imaging Environment: Initial Experience. J Vasc Interv Radiol. 2017;28(8):1098–1107.e1.

22 Abdelsalam ME, Mecci N, Awad A, Bassett RL, Odisio BC, Habibollahi P, et al. Magnetic-Resonance-Imaging-Guided Cryoablation for Solitary-Biopsy-Proven Renal Cell Carcinoma: A Tertiary Cancer Center Experience. Cancers (Basel). 2024;16(10):1815.

23 Morrison PR, Silverman SG, Tuncali K, Tatli S. MRI-guided cryotherapy. J Magn Reson Imaging. 2008;27(2):410–20.

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Tactile Training in Lower-Field Interventional MRI

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Introduction

When the topic of real-time imaging and image-guided procedures is discussed, we rarely think of magnetic resonance imaging (MRI). Ultrasound, X-ray fluoroscopy, and computed tomography (CT) are the modalities most often associated with image-guided interventions, and for good reason. This begs the question: Why hasn't MRI, one of the safest imaging modalities and the gold standard for soft tissue visualization, been more widely adopted for real-time interventions?

Interventional MRI (iMRI) has continuously evolved throughout the history of MRI as a whole [1]. MRI-guided breast biopsies have increasingly become part of the clinical pathway [2, 3]. In the 1990s, interventional procedures in MRI gained momentum, notably through contributions from those such as Ferenc A. Jolesz, M.D., at Brigham and Women's Hospital. Early systems operating at field strength < 1.0T aimed at enhancing neurosurgical procedures and could already demonstrate improved precision and patient outcomes [4, 5]. Subsequent advancements have included specialized system configurations, e.g., ceiling-mounted high field magnets wich can be moved into the operating suite (IMRIS, Deerfield Imaging, Chaska, MN,USA), and dedicated accessory/workflow solutions, e.g., stereotactic frames (ClearPoint Neuro Inc., Solana Beach, CA, USA), to further enhanced MRI-guided neurosurgery.

However, iMRI remains an underutilized modality, and this might be partly attributed to workflow complexity and to a learning/adoption process associated with the transition from a traditional to a new procedural environment. Any interventional procedure requires a group of skilled professionals who each play pivotal and foundational roles in the intervention. The anesthesiologists, the nursing staff, the radiological technologists, and the interventionalists themselves all work toward a successful medical intervention, regardless of modality. Over time, these people and departments have developed, and knowledge has spread so that such procedures are now carried out via consistent, safe, and effective workflows in clinical routine. The goal is to transition these routine workflows to a new environment.

As MRI-guided interventions become more viable with advances in real-time imaging and in low- and mid-field systems, there is a growing need for accessible, tactile training tools that build operator confidence and procedural accuracy. Several groups are concurrently investigating and working with iMRI for a variety of cases and procedures. Our group has investigated and is pursuing a hands-on training approach using low-cost phantoms and real-time MRI guidance on the 0.55T MAGNETOM Free.Max scanner (Siemens Healthineers, Erlangen, Germany).

1 MRI technologist showing a radiography student how to align the target and entry points within the UI.

Developing tools and language

In an effort to democratize and standardize workflows for iMRI, Cook Advanced Technologies and Siemens Healthineers have been partnering to provide a preclinical environment to foster collaboration and interactive learning. Located in West Lafayette, Indiana, a 0.55T MAGNETOM Free.Max system has been fitted to meet the needs of a preclinical, investigational setting. Four MRI display monitors (NordicNeuroLab, Bergen, Norway) on MR-conditional boom arms allow for visualization of images. Prior work also highlighted the need for an MR-conditional wireless headset system to enable continuous communication between the MRI technologist at the helm and the interventionalist and staff in the MR room even during imaging [6]. Bringing all of these components and accessories together is an important aspect toward realization of a true turn-key solution for iMRI to reduce the entry barrier because of potential complex technical integration.

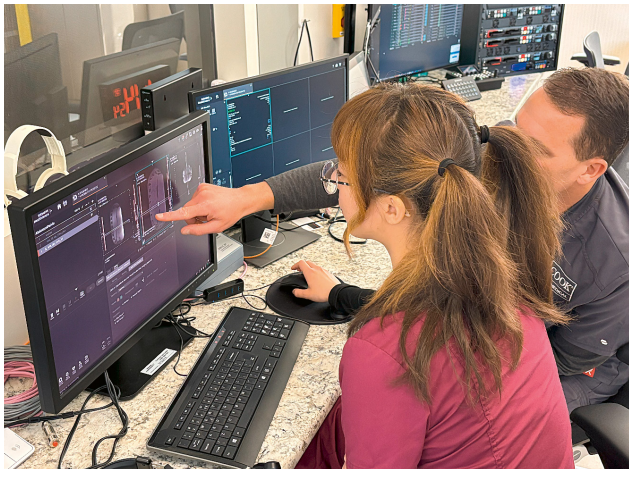
One of the main components of any successful venture is communication. In traditional X-ray-based imaging, users warn others about "X-ray!" When a CT scanner is operating, the warning lights state: "CT is in use". When live X-ray imaging is required, interventionalists call for "fluoro".

The iMRI language is a work in progress, but it should be clear to the users and distinct from X-ray-based procedures. While not industry standard, our collaborative efforts have birthed a unique, agreed-upon language that assists in successful communication. On our dual-monitor setup, the main display unit that the MRI technologist manipulates is referred to as the "Operator", and the second unit that displays imaging and live imaging is known as the "Image". Procedures being performed from the tableside are referred to as "patient side," and those from the back side of the bore are "service side".

In any procedure, the technologist is responsible for the safety of the patient and the personnel in the magnet room. It can be a daunting task, and iMRI language helps to streamline procedures while maintaining safety for all involved. At any time when the patient table might move after sequence commencement, a "table may move" announcement is given. Pinch points on the table are recognized, and staff are alerted to watch hands and fingers. It is imperative that technologists have excellent 3D spatial cognition. If an interventionalist needs to move "up" or "down", good rapport should translate that to anterior vs. posterior or superior vs. inferior. There is some language that technologists and interventional staff will develop naturally in this 3D realm. The most important, universal phrase for any iMRI procedure is "going live".

As the language of iMRI continues to develop, the tools we use are also rapidly evolving to make these procedures possible. The interactive real-time (IRT) imaging user interface (UI)[1] from Siemens Healthineers is a powerful research software tool that facilitates workflow precision and control during iMRI procedures. The extended UI allows the selection of entry and target point, dynamic imaging plane manipulation, and trajectory line overlays. If multiple targets or trajectories are needed, the iMRI UI Extension allows users to set up and save multiple target

[1] *Work in progress. The product is still under development and not commercially available. Its future availability cannot be ensured.*



2 MRI technologist demonstrating the iMRI UI Extension[1] to a radiography student.

3 MRI technologist (blue scrubs) demonstrating the target on the Turducken phantom. The student has now had the experience of both the MRI technologist and the interventionalist.

trajectories and planes. Saved imaging planes and reformats from View&Go can be integrated into the cardiac and vascular UI for quick selection and structured flow through a procedure that follows the interventional devices.

With an intuitive display, users are able to quickly adjust slice position, switch between planes or trajectories, and manipulate certain parameters such as slice thickness and phase encoding direction. The iMRI UI Extension is designed for efficient workflows with minimal delays. It aims to enhance procedural accuracy, reduce learning curves for new users, and support a wide range of applications – from biopsies and ablations to vascular interventions. We decided to put this to the test by inviting untrained radiography students to attempt a simple needle procedure on a phantom and then comparing the times and success rates to those of experienced users. This training has become part of the Indiana University School of Medicine's visit experience for radiography students.

Education for radiography students at Indiana University School of Medicine

Now an annual event, Cook Advanced Technologies welcomes students from the IUSM radiography program to observe, assist, and learn about iMRI. The training principle of "see one, do one, teach one" is easily performed in this preclinical setting. In this vein, we aimed to evaluate a tactile learning model for training both novice and experienced MRI technologists in fine needle biopsy and aspiration techniques. The training model integrated the interactive UI with real-time MRI guidance to assess users' ability to accurately target a phantom lesion within a fixed time frame.

Participants typically include students with zero or limited MRI experience. The needle guidance procedure involves targeting a 2 × 2 × 1.5 cm phantom structure embedded in a multi-layered construct made from discounted grocery store meat – a setup humorously dubbed the "Turducken."

Two roles are assigned and assessed: interface operators (iMRI technologists) at the console, and needle drivers (interventionalists) performing the procedure. The system provided real-time image updates and trajectory feedback. We retroactively collected time-to-target data for the needle drivers. All participants successfully placed the needle into the phantom target, typically within the 5-minute window. In fact, an analysis of nine students and four experienced users demonstrated that all users, regardless of experience level, can accomplish this simple needle task within five minutes.

- **Experienced users** averaged 122 seconds (SD ± 49).
- **Novice users** averaged 230 seconds (SD ± 28).

While experienced technologists required fewer adjustments and completed the task more quickly, novice users also consistently met the success criteria. Feedback highlighted the intuitive design of the UI and its value in helping first-time users conceptualize needle trajectory.

Clinical implications

The results support the ease of using the MAGNETOM Free.Max with a real-time interactive sequence to teach interventional needle guidance. Real-time tactile feedback and image guidance enable rapid learning even for

4 iMRI UI Extension: Technologist interface (left) and iMRI live display (right). With the multiple display option, the technologist can select target and entry points for needle interventions and can manipulate the slice positions in real time. The IUSM radiography students experience both the technologist and interventionalist side of the UI, encouraging a better understanding of their role in the procedures.

inexperienced users. This low-cost, reproducible training method may help broaden the base of MRI professionals familiar with iMRI workflows – potentially catalyzing wider clinical adoption.

The use of this tactile training model using real-time iMRI and the iMRI UI Extension carries important clinical implications. The ability for novice users to quickly develop proficiency in needle guidance suggests that iMRI workflows may be more broadly accessible, aiding the democratization of iMRI. By lowering the barriers to entry, this training approach may facilitate the adoption of iMRI in new clinical environments, potentially expanding the range of MRI-guided procedures beyond highly specialized centers.

Furthermore, as healthcare systems prioritize patient safety and radiation reduction, the inherent advantages of MRI – no ionizing radiation, excellent soft tissue contrast, and real-time feedback – position it as an increasingly attractive option. Incorporating this training model into clinical practice could accelerate the integration of iMRI for biopsies, aspirations, and ablations, ultimately improving patient outcomes through more precise targeting and reduced procedural risk.

Invited physicians

Prior to extending the invitation to the IUSM radiography students, physician feedback on the system was sought. In addition to student training sessions, Cook Advanced Technologies and the iMRI Division at Cook Medical invited several interventional radiologists, surgeons, physicists, and technologists to participate in system demonstrations and hands-on trials. Overall, these physician visits provided critical, real-world feedback on the usability, workflow integration, and clinical potential of lower-field iMRI. Many of the physicians emphasized the importance of an intuitive UI, streamlined setup, and real-time feedback for procedural success. The unique iMRI lab at Cook Advanced Technologies has allowed experts to join the procedure remotely, from across the world. To increase collaboration and communication, experts in Erlangen, Germany can remotely join our training days, being provided with real-time feedback of their system and offering advice of their own to our staff and visitors.

Feedback was optimistic about the system's ability to reduce radiation exposure while maintaining high targeting accuracy, especially for procedures in sensitive anatomical areas. These early physician engagements not only validated the system's clinical relevance, but also helped refine the language, workflow, and UI for broader adoption. Ongoing collaborations with these physicians continue to inform the development of practical clinical protocols and training pathways.

Acknowledgments

We would like to sincerely thank all participating physicians, physicists, technologists, students, engineers, and staff whose time, expertise, and enthusiasm made this project possible. Their collective contributions were essential in refining the workflow, developing effective training models, and advancing the language and practices of iMRI. We extend special gratitude to Siemens Healthineers for their invaluable partnership and support. Their commitment to innovation and to pushing the boundaries of real-time MRI workflows has been instrumental in creating accessible, practical solutions for interventional imaging.

This collaboration has not only fostered technological advancement, but has also helped cultivate a community of learners and practitioners dedicated to improving patient care through safer, more precise imaging techniques. We look forward to continuing this work together as iMRI moves toward broader clinical adoption.

References

1 Barkhausen J, Kahn T, Krombach GA, Kuhl CK, Lotz J, Maintz D, et al. White Paper: Interventional MRI: Current Status and Potential for Development Considering Economic Perspectives, Part 1: General Application. Rofo. 2017;189(7):611–623.
2 Kuhl CK, Elevelt A, Leutner CC, Gieseke J, Pakos E, Schild HH. Interventional breast MR imaging: clinical use of a stereotactic localization and biopsy device. Radiology. 1997;204(3):667–75.
3 Gossmann A, Bangard C, Warm M, Schmutzler RK, Mallmann P, Lackner KJ. Real-time MR-guided wire localization of breast lesions by using an open 1.0-T imager: initial experience. Radiology. 2008;247(2):535–42.
4 Mislow JM, Golby AJ, Black PM. Origins of intraoperative MRI. Neurosurg Clin N Am. 2009;20(2):137–46.
5 Pergolizzi RS Jr, Nabavi A, Schwartz RB, Hsu L, Wong TZ, Martin C, et al. Intra-operative MR guidance during trans-sphenoidal pituitary resection: preliminary results. J Magn Reson Imaging. 2001;13(1):136–41.
6 Amin EK, Campbell-Washburn A, Ratnayaka K. MRI-Guided Cardiac Catheterization in Congenital Heart Disease: How to Get Started. Curr Cardiol Rep. 2022;24(4):419–429.

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Meet Siemens Healthineers

Siemens Healthineers: Our brand name embodies the pioneering spirit and engineering expertise that is unique in the healthcare industry. The people working for Siemens Healthineers are totally committed to the company they work for, and are passionate about their technology. In this section we introduce you to colleagues from all over the world – people who put their hearts into what they do.

Florian Maier, Ph.D.

After earning his degree in computer science from Karlsruhe University, Florian began his career in interventional MRI (iMRI) as a doctoral student at the German Cancer Research Center (DKFZ) in Heidelberg in 2008. Upon successfully completing his Ph.D. in 2012, he accepted a position as a postdoctoral fellow at the University of Texas MD Anderson Cancer Center in Houston, TX, USA, where he continued his work in iMRI. In 2014, Florian returned to DKFZ as a research scientist and, starting in 2016, led its MR-Guided Therapy project group. He joined Siemens Healthineers in 2017 as an application developer and was promoted to Senior Key Expert for MRI-guided therapies in 2023. In 2025, Florian was elected secretary of the ISMRM Interventional MR Study Group.

How did you first come into contact with MRI?
My first hands-on experience with MRI came during my Ph.D. at the German Cancer Research Center (DKFZ) in Michael Bock's lab. I worked on implementing pulse sequences and image reconstruction software for MRI-guided interventions. At the time, we were using a 1.5T MAGNETOM Symphony scanner.

What do you find motivating about your job?
What motivates me most about my work is knowing that our contributions support clinical teams in helping patients. It is incredibly rewarding to see how our innovations support clinicians in their work. I am also deeply grateful to work with so many brilliant and kind colleagues – past and present – whose dedication forms the foundation of what we can achieve together.

What are the biggest challenges in your job?
One of the biggest challenges in my role as Senior Key Expert is balancing a wide range of responsibilities – being actively involved in numerous topics, supporting multiple collaboration projects at partner sites, and carving out focused time to drive predevelopment initiatives forward. That said, it is incredibly rewarding to see research software successfully deployed at collaboration sites, and to see work-in-progress features eventually integrated into our products.

What do you think are the most important developments in healthcare?
In the field of iMRI, I see a great opportunity for the technology to evolve from a niche application used primarily in research-focused university hospitals to a widely adopted clinical tool. I believe our close collaboration with Cook Medical could be a key enabler of this transformation. By combining high-quality MR imaging with advanced MR-compatible interventional tools in a single, integrated solution, we have the potential to overcome one of the major barriers to broader adoption. I am excited about the prospect of seeing advanced iMRI procedures become part of the standard of care in the near future.

What would you do if you could spend a month doing whatever you wanted?
Earlier this year, I had the opportunity to spend several days at Cook Advanced Technologies in West Lafayette, IN, USA, collaborating with Jesse Roll and the team on predevelopment projects. The experience was both highly productive and intellectually stimulating. If given the chance to spend an entire month as I choose, I would gladly dedicate it to deepening that collaboration and further advancing our joint innovation efforts.

Axel Krafft, Ph.D.

Axel Krafft graduated in physics from Heidelberg University, Germany, where he also obtained his Ph.D. in 2010. During his time as a diploma and Ph.D. student at the German Cancer Research Center in Heidelberg, Axel was already working in the field of interventional MRI research. There, he developed sequence and hardware concepts for device tracking and MR thermometry under the supervision of Professor Michael Bock. In 2011, Axel moved to Memphis, TN, USA, and joined the MR Physics group of Claudia Hillenbrand, Ph.D. at St. Jude Children's Research Hospital as a staff scientist to work on methods for ultra-short-echo-time (UTE) imaging and quantitative T2* assessment in the liver. Axel relocated to Germany in 2014. There, he continued his research in the field of MRI under Professor Jürgen Hennig in the medical physics division of the Department of Radiology at University Hospital Freiburg. In Freiburg, Axel initially worked as a research associate in experimental radiology and eventually led an independent research group in cardiovascular MRI.

In 2019, Axel joined Siemens Healthineers as an application developer for interventional cardiac MRI, a role that allowed him to draw on the expertise gained during his work in academia. Since 2023, he has been a solution owner in the MR Therapy team (headed by Arne Hengerer, Ph.D.). In this role, he is responsible for product management and definition in the field of interventional MRI, including MRI-guided percutaneous and (cardio)vascular procedures. Axel's recent work has focused heavily on expanding interventional MRI to 0.55T.

How did you first come into contact with MRI?
My first encounter with MRI was as a patient when I needed a brain scan after an accident in high school. However, my first, more deliberate contact was when I saw a job opening for a diploma thesis project in Michael Bock's lab at the German Cancer Research Center in Heidelberg. When I started my studies in physics back in 2000, I planned to eventually specialize in astronomy. But during my second or third year, some special courses on medical imaging caught my attention and I decided to specialize in medical physics. The actual topic of my diploma project was on tracking techniques for a robotic assistance system in MRI. I found this pretty cool because it included a bit of everything: hardware, some programming, and lots of MR scanning. After that, I was bitten by the MRI bug, and today I am still fascinated by all the possibilities MR imaging offers.

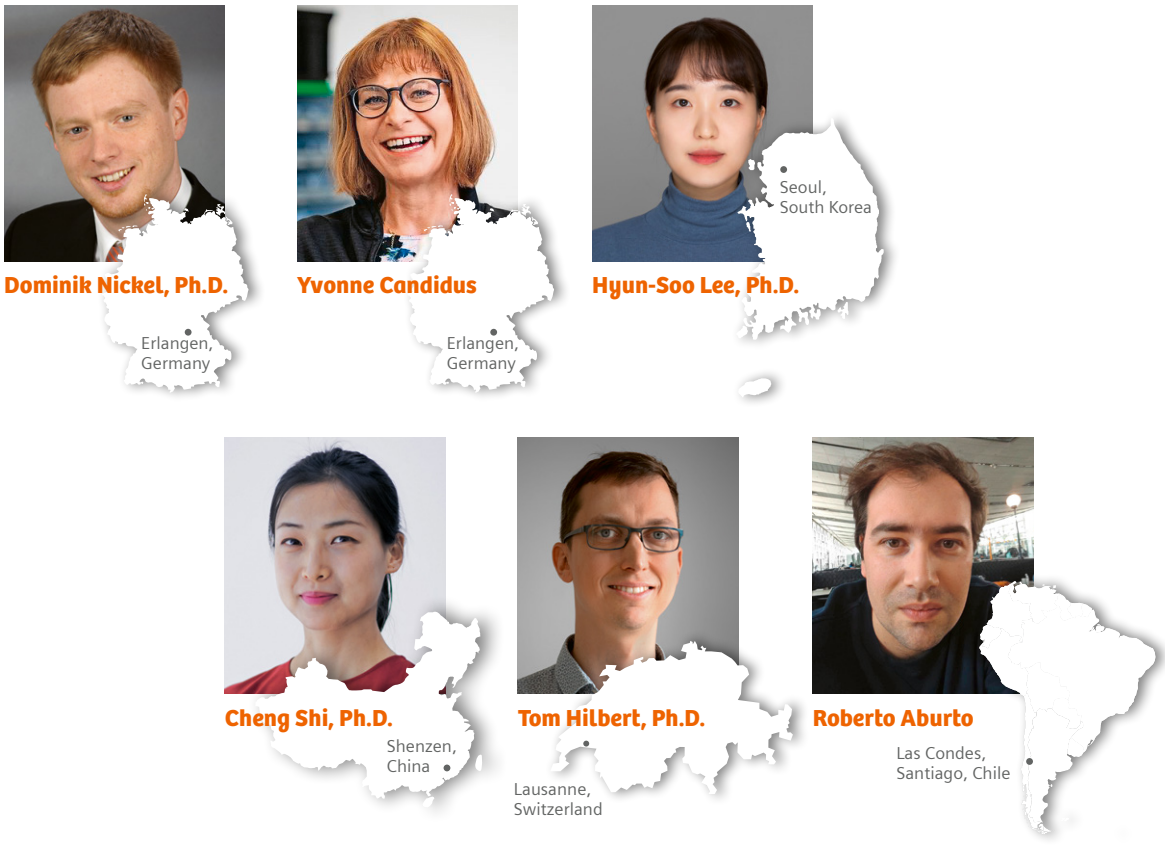
What do you find motivating about your job, and what are in your opinion the most exciting developments in interventional MRI?
While our job and everyday obligations are sometimes challenging and demanding, I am grateful to work for Siemens Healthineers in the field of interventional MRI. It allows me to bring all the expertise that I've gained over the years in different locations and settings into my daily work. In our field, we have the chance to develop something which can have a direct impact on patients. One striking example for me is the treatment of arrhythmia, which is also done in the MR environment in a few specialized centers. After successful treatment, the patient can literally leave the hospital without any disorders. The opportunity to contribute to such developments and work with our collaborators and partners on improving patient care is something I find motivating and rewarding.

To me, the most exciting development in our field comes with our "new" field strength of 0.55T. Interventional MRI is nothing new and probably goes back more than 25 years. Clinicians recognized the value of MRI in the context of interventions (lack of ionizing radiation and excellent soft tissue contrast are just two of the many benefits) some time ago. Still, interventional MRI was in some sort of chicken-and-egg state: lots of potential, but also lots of challenges, such as making device (needles, catheters, etc.) safely usable in the MR environment. With 0.55T, there is a great opportunity for reducing the technical entry barrier into the MRI environment, and this might truly help solve the chicken-egg problem. With that in mind, I am very excited to see how our strategic partnership with Cook Medical evolves, and hopefully we will jointly expand interventional MRI. The fact that a larger device manufacturer has entered the interventional MRI space has gained a lot of attention in the field. To me, these are very exciting developments.

What would you do if you could spend a month doing whatever you wanted?
Well, I think this depends a little and I don't have one clear answer. While my job allows me to interact with our clinical partners quite frequently – we even occasionally have the chance to observe clinical work when visiting our partners – I can imagine that a "look behind the scenes" when working with a clinical team for a longer amount of time would be extremely valuable. A second aspect (also work related) is that our daily obligations rarely allow us to explore ideas and concepts without interruptions. Having one month to do that would be great.

Outside of work, I think I would travel with my family. I traveled to New Zealand for a two-month hiking and backpacking trip after graduating. It would mean a lot me if I could take my family and visit some of the places again with them. But even one month might be a bit short for such a long trip, so perhaps I would simply try to spend time with family and friends. And one last idea: Windsurfing is on my bucket list. I'm just not sure if one month would be long enough to learn, though.

Get to know us



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