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Enabling Technology for MRI-Guided Intervention

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Abstract

The use of MRI for image guided intervention poses both great opportunity and challenges. While MRI is distinguished by its excellent contrast resolution and lack of ionizing radiation, It wasn't till the 1990s that technologic innovations allowed for adoption of MRI as a guidance modality for intervention. With advances in magnet, protocol, coil, biopsy needle and ablation probe design, MRI has emerged as viable, and increasingly, preferable alternative to other image guidance modalities. With the development of targeting software, augmented reality, robotic assist devices and MR thermometry, the future of MRI-guided interventions remains promising.

The use of MRI as a guidance-modality has been made possible by a series of technologic innovations. These “enabling technologies” have allowed MRI to emerge as an alternative to more traditional ionizing (fluoroscopy, CT, CT-fluoroscopy) and non-ionizing (ultrasound) modes of imaging guidance (1). These modalities once held significant advantages to MRI, with dramatically shorter acquisition times allowing for real time intraprocedural imaging, without the no need for bulky coils or specialized MR-compatible devices. However, innovations in protocol and coil design have mitigated these factors, and increasing magnet strength has further enhanced MRI's notable advantage in soft tissue contrast resolution (2). In this review we discuss specific technologic advances in in magnet, protocol, coil, biopsy needle and ablation probe design that have made MRI a viable image-guidance technique. Further, we discuss continuing innovations in targeting software, augmented reality, robotic assist devices and MR thermometry that promise to expand the clinical applications for MRI-guided intervention.

MRI Systems

Initial efforts to utilize MRI-guidance led the development of multiple specialized closed specialized vertical gap systems (1). These systems exchanged the field strength of closed bore systems for unprecedented patient access. The first, and most popular of these specialized designs was the 0.5T “double doughnut”. Using 2 60 cm bore magnets and an intervening 58 cm vertical gap, this innovative design allowed the operator access to the patient at isocenter, without repositioning the patient (3). 15 of these systems was were ultimately deployed and were utilized in an array of applications, including neurosurgical procedures, breast conservation surgery, renal, liver and MSK biopsies and thermal ablation procedures (4).

While several subsequent open iMRI systems were developed and had limited clinical success, diagnostic image quality continued to be a dilemma due to low field strength. Thus, with open bore systems serving as a proof of concept, diagnostic closed bore scanners were reintroduced, becoming the workhorse of modern MRI guided intervention (5). This shift has been driven technologic innovation, with the first 3-T debuting in 2004, offering significant improvements in contrast resolution and signal to noise compared to its 1.5-T predecessor (6,7,8). Subsequent innovations in magnet design have allowed for simultaneous increases in bore diameter and decreases in bore lengths, minimizing the need for patient movement and making in bore feasible. Currently, multiple vendors offer 3T systems with 70 cm bores and lengths as short as 125 cm, allowing improved operator access while preserving image quality.

Protocols

One of the early challenges in adopting MRI as a guidance modality was balancing the inherent tradeoff between contrast resolution and scan time. This dilemma led to the development of rapid pulse sequences, allowing practitioners to localize a lesion, determine an approach and monitor therapy, all in real-time (9). Breath-hold fast T2-weighted spin echo techniques such as HASTE (half Fourier acquisition single shot turbo spin echo), and variable weighting gradient echo sequences such as FLASH (fast low angle shot) and SSFP (Steady-state free precession) have all been successfully utilized in providing intermittent imaging guidance (Fig 1). The ability to select from multiple pulse sequences further enhances MRI's advantage in contrast resolution, as altering the degree of T1/T2 weighting allow visualization of lesions or vital structures that may otherwise be occult (10). SSFP has reduced imaging times to the extent that fluoroscopic MRI can, for most indications, provide sufficient contrast and temporal resolution to serve as a real-time imaging modality (11). Using this technique fluoroscopic MRI guidance has successfully been utilized in guiding both diagnostic biopsies and thermal ablations (12,13).

Coils

The need for surface coils is a challenge unique to MRI-guided intervention. While tailored MRI interventional coils remain primarily within the research realm, advances in diagnostic body coil design have benefited operators of MRI-guided intervention. Reductions in the size and rigidity of body matrix coils has made it possible to place biopsy needles or ablation probes in-between array elements (14) (Fig 2). In other applications a body coil may be utilized only for lesion localization and replaced with a smaller, precisely placed flexible loop coil (15). In certain instances, built-in spine coils may be sufficient for intervention guidance, as advances in MRI field strength and pulse sequences provide adequate signal even in the absence of additional surface coils (16).

Biopsy needles and ablation probes

One of the chief limitations to the adoption of MR-guided intervention was the absence of approved MR-compatible devices. Initial non-ferrous alternatives (most commonly titanium alloy) exhibited different physical properties from their traditional stainless steel

counterparts, and were more prone to failure and deformation (17,18). This has subsequently changed, with a plethora of new MR-guided biopsy needles and ablation probes rivaling their stainless steel counterparts in performance (19, 20). These devices run the full gambit of thermal ablation modalities (RF, microwave and cryoablation) and more novel techniques such as high frequency ultrasound (HIFU) and laser interstitial thermal therapy (LITT). The most recent generation of devices have been optimized for high field strength closed bore magnets, resulting in predictable susceptibility pattern and allowing for visual visualization of the device without obscuring nearby anatomic structures (21). Additionally, new techniques, including passive tracking using applied electric currents (22) and active wireless tracking (23) have shown promise in aiding device localization.

Future Directions

Technologic advances have made MRI a viable guidance modality and its use in breast, prostate, and MSK biopsies and thermal ablation procedures is well established (4). The use of MRI-guidance has relied on specialized devices and techniques designed for each specific clinical application. In the case of breast and transperineal prostate biopsies, this commonly involves the application of plastic grids with fiducial markers, both stabilizing and localizing lesions of interest (24,25) (Fig 3). While these current, primarily operator driven, techniques have proven effective; new innovations in software and robotics, tailored to specific interventional MRI applications, promise to further increase the ease and effectiveness of MRI-Guided interventions.

A number of novel software solutions are available to aid in lesion localization and targeting. One commercially available package (DynaTRIM, Invivo) allows registration prostate a lesion based on multiparametric MRI and targets the lesions using an in-bore biopsy needle with built in fiducial marker (26). Similar, open-source methods of image registration have been successfully utilized to fuse DWI images to intraprocedural sequences, aiding in lesion localization (27). Similarly, in breast intervention multiple commercial vendors offer computer aided detection software that aid in determining needle entry site and depth after a lesion is selected by the operator (28).

Leveraging computational planning data, augmented reality systems fuse the intraprocedural target lesion with MRI images, projecting extrapolated trajectory data into the operator's workplace or headset. This obviates the need for the operator to extrapolate imaging-data intraprocedurally, a time consuming and potentially error prone process. Early experience with these augmented reality techniques have shown promise in both MSK spine (30) and neurosurgical applications (31).

MRI-compatible robots utilize localization and targeting data to allow remote or operator assisted needle introduction. This method promises to reduce error inherent manual needle introduction techniques, and increase accuracy and efficiency (Fig 4). While robotic devices are still in early research stages, initial experiences with these devices has been encouraging, with positive results in both breast (32) and prostate applications (33,34).

While secondary changes from thermal ablation are apparent on all imaging modalities, MR thermometry is unique in its ability to generate a localized heat map. These sequences have shown particular promise in heat-based thermal ablation, where the ablation zone may be difficult to visualize, and minimizing damage to normal tissues and adjacent vital structures is paramount. While still limited in clinical use, MR thermometry sequences have been successfully utilized as a method of feedback control for LITT (35) and has been validated as a monitoring method for high intensity focused ultrasound (HIFU) (36) and cryoablation (37). Additionally, automated segmentation offers an alternative method for feedback control, showing early promise as a monitoring tool for cryoablation (38).

Conclusions

Thanks to a series of technologic innovations, MRI-guided intervention is now successfully employed in a broad array of clinical applications. With many new “enabling technologies” in development, the future of MRI-guided intervention remains promising.

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Fig 1.
Intraprocedural HASTE images demonstrating RCC (a), cryoablation probe (b) and iceball (c).

Fig 2.
3-T body matrix coil (a) optimally positioned with skin target centered between coil array elements (b).

Fig 3.
Patient positioned for transperineal prostate biopsy with plastic template in place.

Fig 4. Renderings of a robotic assist device (*Cannon, USA*) (a) and accompanying software interface (b).