

# Magnetic Resonance Imaging Guidance For Interventions

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## Introduction

Magnetic resonance imaging (MRI) has several unique attributes that can be exploited for guiding minimally invasive interventions. Among these are its inherent high tissue contrast and the ability to manipulate contrast differences using various pulse sequences (or contrast agents), multi-planar imaging capability, and avoidance of ionizing radiation. There is, however, an inverse relationship between spatial and temporal resolution. Nevertheless, in addition to detailed anatomic information, MRI also provides physiological information on blood flow, tissue perfusion and diffusion (functional imaging), and temperature changes that can be used for monitoring therapy.

Industry has responded to the never-ending demand for minimally invasive therapies that have the potential for reducing morbidity and cost, by developing various dedicated interventional-MRI (iMRI, open MRI scanners) machines that allow freer

access to the patient than had been available with the conventional (closed) diagnostic scanners (1-3). Radiologists, for their part, have developed several promising therapeutic devices and strategies for a variety of applications. Some of these procedures may be performed on conventional machines and others require the dedicated open-access units. The commercially available iMRI units and the requirements for an ideal facility (including anesthesia) have been described previously (1-3). In the interest of brevity, this presentation will focus on the current status of the various therapeutic applications and related devices under development.

### Current Limitations

Conventional interventional procedures have four stages: access (to the vessel or organ), guidance to a remote site of interest, therapy, and monitoring. In spite of the developments described below, to date with rare exceptions (4,5), MR has not been simultaneously employed as the sole imaging modality for access, device guidance, and monitoring of therapy. One other additional modality has always been needed. Open-surgical procedures utilizing MRI-guidance obviously offer direct visual feedback. On the other hand, ‘percutaneous’ procedures have required either x-ray fluoroscopic, CT Scan,

sonographic, or endoscopic guidance for initial access and/or guidance of device placement (3,6).

Regardless of the therapy contemplated, the usual contraindications to placing a patient in the MR environment pertain. Implanted metallic devices will cause artifacts that degrade images in their vicinity and in some instances local heating may occur. The presence of a cardiac pacemaker remains a major exclusion criterion because of the risk of malfunction. Open- (neuro) surgical procedures require full anesthesia support, but most of the less invasive procedures may be performed with conscious sedation alone. Anesthesia machines for use in MRI suites are now commercially available (3). Nevertheless, in as much as sophisticated monitoring devices are now available, EKG signals are distorted by the magnetic field and unreliable for diagnosis of ischemia. Thus, patients for whom this may be a problem are excluded.

MRI allows considerable flexibility in tailoring imaging protocols to suite the specific application, but physical realities dictate a trade-off between spatial and temporal resolution. Thus, although image guidance needs only to be as sophisticated as the application requires, device visualization is still sub-optimal. If one wishes to perform a biopsy or drainage procedure on relatively large lesions in a staged manner, as is done currently with CT-

scanners, then the lack of continuous guidance for instrument placement is not a hindrance. In fact, such 'MR-guided' procedures were performed over a decade ago on conventional MR scanners (7,8) using passive device visualization (i.e., relying on the image artifact created by the device). On the other hand, if one wishes to emulate the real-time spatial and temporal precision of present-day x-ray fluoroscopy-guided procedures, one quickly realizes that MR is still in its infancy.

Thus, clear indications for MRI-guided interventions presently exist only for those applications where there are few other alternatives (e.g., head and neck surgery) or when accessible lesions can only be adequately visualized and/or their treatment monitored by this modality (9). Technology has to evolve so that MRI becomes a one-stop modality for diagnosis, access, guidance of instruments, and monitoring of therapy.

## Device Visualization, Tracking and Navigation

Using MRI for initial access to small targets such as superficial blood vessels will be possible when visualization of devices in general is improved. Clearly, visualization and tracking/navigation are important for guiding devices to remote lesions once access has been gained. This, being the bigger of the

two problems, has received more attention. Visualization of devices can be either *passive* or *active*. For passive visualization, one simply relies on the artifact created within the image by the device material and the displacement of adjacent signal-producing tissues. Such devices are usually manufactured from non-ferromagnetic materials, but the size of the artifact nevertheless depends upon the device material, diameter, and pulse sequence used (10). However, clever reconstruction algorithms that rapidly refresh the critical portions of the image allow continuous 'near real-time guidance' of passively visualized devices (11, 12).

The visibility of passive devices can be enhanced by the incorporation of paramagnetic markers that produce localized susceptibility artifacts. For example, angioplasty methods with near real-time imaging (1 frame/sec) have been developed and tested *in vitro* with catheters impregnated with dysprosium oxide (13) and also successfully tested for tracking in human veins (14). Catheters employing similar principles have been used for the placement of an IVC filter (15) and a biliary drainage catheter in a pig (16). One limitation of such catheters is that only their marked tips are visible and there is no feedback on the status of the proximal portion of the catheter.

In another variation of passive visualization, gadolinium-filled off-the-shelf catheters have been tracked accurately in *in vitro* models using real-time (3 frames/second) monitoring. These catheters can be visualized throughout the imaged volume and have been tested for performing renal artery PTA in a pig (17) and aneurysm coiling in a canine model (18).

The use of passively visualized devices is technically challenging and time-consuming. Stent placement in humans without real-time image guidance, but with only passive device visualization has been fraught with difficulties ranging from inadequate visualization of catheters and stents, to prolongation of treatment time (mean of 74 minutes), and complications such as subintimal dissection and stent misplacement (19). Additionally, safety is an issue because metallic guidewires/devices experience significant heating, depending upon the length of the wire exposed to radio-frequency excitation and the imaging pulse-sequence employed (20-22).

One other means by which passive devices may be tracked is by using optical navigation. This is achieved by placing two or three light-emitting diodes (LED) on the rigid frame of a needle (or device) holder (4,23). Television cameras mounted on the scanner monitor the positions of the LED reference points. This real-time positional information is cross-registered with the image frame-

of-reference allowing interactive control of the scan plane as well as monitoring of needle advancement on the image which is refreshed every 1.5 seconds. These basic strategies, which were initially used for radiologist-guided neurosurgical procedures, have since been expanded to needle biopsy (4) and drainage with over-the-wire exchanges (5) elsewhere in the body. Clearly, such systems are reliable only for rigid tools that do not bend. However, needles do cantilever from the rigid frame and for some applications deviations off the target by almost a centimeter have been reported (9). Optical navigation methods are not suitable for endovascular procedures since they are performed with flexible devices.

One solution for visualizing flexible devices that follow tortuous paths is to incorporate a thin copper wire onto the catheter, so that when a current is passed through this wire, a signal void is created by the induced local field homogeneity (spin dephasing) (24). Such catheters are highly visible on fast gradient-echo pulse sequences. The size of the artifact varies with the amplitude of the current. However, continuous tracking of such devices needs further development and safety is also a consideration since local heating and possible burning may occur (20-22).

Active visualization and tracking can be accomplished by mounting a micro receiver-coil at

the tip of a flexible catheter (25-27). The coil detects the local resonant frequency as it moves through a linear magnetic field gradient superimposed over the main magnetic field. The measured frequency is then decoded to determine the position of the coil. All three spatial coordinates can be determined by switching the linear gradient to coincide with each of the three orthogonal axes. The path traversed by the tip can be 'tracked' by overlaying the positional information onto a previously acquired 'road-map image'. In addition, the orientation of the catheter in three-dimensional space can be determined by the judicious placement of two or three independent coils. These same coils may also be used to produce local micro-images. The use of these catheters has been primarily confined to animal experiments and bench-top experiments (26,28). Preliminary work has included TIPS creation in a pig model (27). One human study has used active biplane tracking for performing biopsies in human (29). Another version of an active tracking/imaging catheter utilizes a loopless antenna (MR imaging guidewire) (30). It has been tested successfully for performing supra-renal aortic (model stenosis) angioplasty in rabbits (30). Success was gauged by assessing improved renal perfusion following angioplasty. Again, all active coils have the same heating-related safety issues

discussed previously, and need to be thoroughly evaluated prior to routine human use (31).

Dedicated imaging catheters are the most sophisticated and complex of the MR devices developed for endoluminal diagnosis and therapy. These catheters produce exquisite high-resolution images of the wall and adjacent structures. Several variations of imaging catheters have been designed and tested (32-34). Designs in which a receiver coil is placed in an angioplasty balloon are sub-optimal since blood-flow is occluded during imaging. In fact, one limitation with these imaging coils has been that the coil has to be almost of the same diameter as the vessel in order to get adequate visualization of the wall and surrounding structures. However, there are technical solutions to these problems. The active tracking method discussed above can also be adapted to aid in guiding these imaging catheters to the desired location.

### Advances in Rapid MR Imaging.

It should be noted that there have also been considerable advances in diagnostic MR imaging along with developments in interventional MR technology. Today, conventional MRI scanners allow remarkably rapid image acquisition, reconstruction and display. Motion-related artifacts (primarily

respiratory and cardiac) have been largely overcome by the newer rapid image acquisition protocols. Echoplanar pulse-sequences now allow sub-second imaging. High-quality MR angiography is routinely performed at many centers. MR fluoroscopy is available at a few centers with active R&D programs or industry collaborations (35,36). The blurriness of the images may be disconcerting to some – not unlike sonographic images are to the novice. When the image refresh-rates are too slow, device motion appears jerky. Fortunately, the limitations of physics are slowly but certainly being surmounted by newer image processing algorithms pushing fluoroscopic imaging at 20 frames/second (37). Such real-time MR fluoroscopy has been successfully tested for placing iliac artery stents in pigs at an average time of 6 minutes for deployment (37).

## Other Developments

The first open iMRI machines were developed primarily to aid neurosurgical procedures by allowing visualization of tissues adjacent to the operative site. For this historical reason, and since the structures of the head and neck are relatively stationary, the early developmental work on instrument guidance and monitoring of therapy was focused on neurological applications. As such, the worldwide experience with

head, neck and spine interventions (e.g., craniotomies, biopsies, cyst evacuations, trans-sphenoidal resections, peri-radicular therapy, etc.), although limited to a few centers, now numbers in the thousands (9,38,39)

There has also been considerable progress in computer-assisted surgery through the integration of iMRI with other imaging modalities such as CT-Scan and SPECT (image fusion) (38). Such sophisticated approaches provide feedback about instrument placement and critical functional tissues adjacent to the planned surgical target. Some of these image-processing advances have been applied clinically for targeting and monitoring therapy during cryoablation of liver tumors (6,38), open prostate biopsy (40), brachytherapy planning and seed placement for prostate cancer (41), and for focused ultrasound (FUS) thermo-ablation of breast adenomas (6,38)

However, many MR-guided procedures have also been performed on conventional scanners, without sophisticated navigational tools, employing only passive visualization of devices/needles. For example, biopsy of liver lesions, not near the dome of the diaphragm, has been done successfully using respiratory-triggered high-resolution T2-weighted image sequences (42). This imaging protocol reduces the size of the needle artifact relative to the faster gradient-echo sequences and allows more precise

needle placement. Similarly, large-core (14G) needle biopsies of small lesions of the breast, visible only on MRI, were obtained utilizing a MR-compatible stereotactic unit in a conventional closed MR scanner (43).

Navigational tools and close patient access are also not necessary for easily accessible lesions, and in such cases MR imaging is used primarily to monitor therapy. One example is the placement of needles into superficial lesions such as low-flow vascular malformations of the head and neck using MRI for monitoring direct percutaneous sclerotherapy (44). Similarly, selected superficial breast lesions have been accessed by conventional needle placement and ablated with different forms of thermal therapy with MRI monitoring (45). Others have attempted to ablate small renal tumors (albeit without histological diagnosis) with cryotherapy by placing probes under passive visualization (46).

MRI shows great promise for monitoring thermotherapy. The different forms of thermotherapy monitored with MRI include heating with radio-frequency, lasers, microwaves and focused ultrasound, as well as freezing with cryotherapy. Each of these merits a long discussion of its own which is beyond the scope of this presentation. Suffice it to say that each has its own nuances and

limitations, and MR thermometry is an active field of study (6,47-49).

## Conclusion

MR has the potential to be a powerful once-stop modality for diagnosis, device guidance and monitoring of therapy. The range of image-contrast mechanisms and sensitivity to temperatures changes endow MR with an almost limitless ability to monitor all forms of treatment from open-surgery and solid tumor ablation to endoscopic and endovascular interventions. All of these treatments are in their developmental stages, and few if any are widely or routinely used. Thermal therapy still needs to be accurately controlled at the margins. As for devices, those that can be used with rigid guides can be tracked with optical navigation. The same is not true for devices for vascular intervention that remain in the prototype stage. Safety issues related to inadequate visualization and potential burns from heating of metallic devices have to be solved. As such, MRI's main strength today is its ability to monitor ablation therapy related changes in tissues. In some cases, MR offers a complementary form of image guidance, and only the rare procedure has been done exclusively with MRI guidance. This is not to

minimize interventional-MRI's potential, but to highlight the present deficiencies that need more focused attention from all radiologists, and especially interventional radiologists, in order to make the promise of iMRI a reality. Radiologists should not become mere passive participants in "radiologist-guided" surgical procedures, but rather should strive to be the sole deliverer of diagnosis, guidance, therapy and monitoring. For MRI to replace present-day interventional radiology procedures, it has to diagnose, guide and monitor therapy in a cost-effective manner (50). This future is for those who make it happen.

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