Intraoperative and interventional MRI: Recommendations for a safe environment’

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Abstract

In this paper we report on current experience and review magnetic resonance safety protocols and literature in order to define practices surrounding MRI-guided interventional and surgical procedures. Direct experience, the American College of Radiology White paper on MR Safety, and various other sources are summarized. Additional recommendations for interventional and surgical MRI-guided procedures cover suite location/layout, accessibility, safety policy, personnel training, and MRI compatibility issues. Further information is freely available for sites to establish practices to minimize risk and ensure safety. Interventional and intraoperative MRI is emerging from its infancy, with twelve years since the advent of the field and well over 10,000 cases collectively performed. Thus, users of interventional and intraoperative MRI should adapt guidelines utilizing universal standards and terminology and establish a site-specific policy. With policy enforcement and proper training, the interventional and intraoperative MR imaging suite can be a safe and effective environment.

Key words: Interventional MRI; intraoperative MR, MR safety, image-guided therapy, MRI

Introduction

Magnetic Resonance Imaging (MRI) has been shown to be invaluable for guiding and monitoring interventional and surgical procedures, as it is a multi-planar cross sectional modality with exquisite soft tissue contrast. The appeal increases due to the absence of ionizing radiation and lack of need for a nephrotoxic contrast agent, as well as its ability to elucidate tissue changes due to thermal therapies (1). The use of an MRI scanner, a powerful magnet, in the interventional setting poses challenges in ensuring a safe environment for the patient and staff. Moreover, energy associated with image acquisition has the potential to cause heating in conductive objects and in the patient himself. Many safety guidelines for interventional and intraoperative MRI (iMRI) are based on safety protocols for diagnostic MRI. However, particular care is necessary to enhance these guidelines for MRI-guided interventional or surgical procedures. Safe behavior can be engrained into personnel by training and policy enforcement. Alternatively, safe behavior can be coerced by measures such as suite layout and restriction of access. In this paper, these two means will be illustrated and specific recent recommendations and site experience for interventional MR departments will be summarized (2–4).

Safety via design

Architectural considerations

Safety begins before the MRI scanner is even installed. The location and layout of an iMRI suite must be planned not only for workflow issues, but also for safety (4,5). With an increasing number of scanners being installed in locations outside of the diagnostic radiology area, training alone will not ensure safety. Unlike in the diagnostic MRI area,
personnel may not be aware of the risks of magnetic field attraction and effects of the fringe field on implants.

To limit risk of untrained personnel entering the iMRI room, it is ideal to locate the scanner in a dedicated suite. If the scanner is to be located in the operating room, interventional radiology, or catheter lab complex, the scanner should be in an isolated area without general access. To further limit access, only one entrance into the iMRI room should exist. The ideal location for a door is near the console area where it is within direct line of sight of the MRI technologist or other trained personnel (Figure 1). Security cameras installed at the entrance to the suite and MRI room enable the MR trained staff to further monitor access and activity.

Choice of MRI scanner and procedural flow

Several scanner configurations are currently used for iMRI procedures. The choice of scanner may strongly influence architectural considerations and how the imaging and intervention are performed. Solutions for iMRI include

- moving the patient into a conventional closed bore or horizontally open scanner by translating or pivoting a table up to 180° to allow the head of the patient to be placed outside the 5 Gauss line,
- moving the closed bore scanner to the patient,
- operating within a vertically open scanner from which there is no need to move the patient, or
- using a dedicated portable scanner (Figure 2a–d).

Certain procedures are enabled by the capabilities of the scanner. The higher field closed bore scanners have inherently greater signal to noise ratio images and faster imaging, which are necessary for cardiac and vascular applications (6–8). The high field scanners, moreover, have greater sensitivity to temperature changes during thermal ablations, which is ideal for procedures such as focused ultrasound ablation (9,10). Lower field open scanners offer greater access for therapeutic probe placement. The tradeoffs of these scanners are listed in Table I.

Complexity of controlling access increases in the situation where a single iMRI room services multiple operating rooms (Figure 3 a–c). Depending on layout, more entrances into the iMRI room may be necessary. Moreover, moving an intubated patient between the surgical station and the scanner poses a clinical safety concern. Safety concerns with single room solutions, where the procedure occurs within the iMRI room away from the scanner, will be discussed later.

Site access restrictions

Signs, with warnings of the risks associated with the MRI scanner, are necessary but in reality are seldom effective. Physical barriers such as locked doors and limited entrances are crucial to restrict access to the iMRI suite (Table II). All of the concepts that apply to restriction of access and zoning in diagnostic MRI also apply to the iMRI suite and can be read elsewhere (2,3) in this special issue. Zone 3 (area immediately outside the scanner room) must be extended to encompass the substerile corridor and support space outside the scanner room. If operating rooms adjoin the iMRI room, the operating room may undergo a change of zone designation based on use and barriers. If an OR is open to the iMRI room, it must also be considered Zone 4 (MR scanner room). If a door between the iMRI room and OR is closed, the OR becomes part of Zone 3. If passage between the OR and Zone 2, Zone 3, and Zone 4 is eliminated, the OR may be designated Zone 1 (outside the MR suite). Zone 3 should be restricted. Keycards, keys, or numerical codes are means of limiting access to only trained personnel. Many disciplines involved in iMRI must be MR safety trained, however, to limit potential hazards; a site-specific policy should be developed to determine which personnel should have access and which should be escorted into the suite (Figure 4).

Safety via policy

Safety training

Before a procedure in iMRI can be attempted, a multidisciplinary team must be designed to
Figure 2. Possible solutions for patient positioning for interventional or surgical MR-guided procedures: (a) moving the patient into a conventional closed bore or (b) a horizontally open scanner by translating or pivoting a table; (c) operating within a vertically open scanner (GE Signa SP 0.5T-MRI) that permits access to the patient during imaging by a 56-cm gap; LCD screens to monitor imaging data during a procedure are mounted on both sides of the work area at eye level; MR-compatible anesthesia equipment and MR-compatible instruments can be placed nearby, thus there is no need to move the patient; (d) or with use of a dedicated portable vertical 0.12 Tesla scanner (PoleStar N-10, Odin Medical Technologies, Inc; Newton, MA) that uses a pair of ceramic permanent magnets spaced 25 cm apart (Figure 2a, Courtesy of Siemens Medical Systems, Figures 2b and 2d, Courtesy of Case Western Reserve University, Cleveland, Ohio).
formalize a safety policy for the suite. A mechanism must be set up to communicate the policy to personnel. On-line or written testing in addition to practical training is mandatory and must be annually renewed at some facilities (4).

Screening

Patient screening must be conducted by an MRI safety trained staff member (11,12). The screening form should help to rule out contraindications for MRI scans such as pacemakers, some aneurysm clips, metal fragments in the eye, mechanical device implants (e.g. drug infusion pump, neurostimulator). Personnel who work in the iMRI suite should be subject to the same screening procedure. However, since the personnel will not be imaged, some contraindications (e.g. tattoos, medication patches) do not need to be considered.

Patients should change into a hospital gown and remove hearing aids, hairpins, barrettes, jewelry (including body piercing), watches, and medication patches prior to entering the iMRI room. At some centers, personnel are required to wear pocketless scrubs to decrease the likelihood of ferrous objects entering the scanner room.

Patient positioning

In many iMRI cases, the patient will be under general anesthesia and unable to move. It is essential that the patient is positioned properly and all pressure points should be appropriately padded to maintain good circulation. In neurosurgical cases where the head is pinned in a head holder, trade-offs must sometimes be made between centering the patient in the suite spot of the imaging volume and positioning the patient in the ideal surgical position. Necessary padding, with larger patients, can sometimes prohibit fitting the patient into the bore of the scanner.

Padding must also be used to eliminate closed loops created by skin-to-skin contact or contact with the skin and an ECG cable or the cable of the MRI coil (Figure 5). The integrity of the insulation and/or housing of all components, including coils, leads, cables and wires need to be checked regularly.

A patient-warming system can be used to maintain body temperature by placing the heater in the room adjacent to the iMRI room and introducing the hot air tubing into the room via a penetration panel. Compression boots to maintain circulation can be used with a similar method.

Static magnetic field and iso-gauss lines

The magnetic field decreases with distance from the scanner. Closed-loop lines of iso-gauss (constant magnetic field strength) exist, and can be drawn on the floor of the iMRI suite to serve as a warning to staff. The criterion of the 5-Gauss (G) (0.0005-Telsa) line was established early to limit long-term occupation exposure. The 5-G line must be contained within the MRI room. The line also serves to limit exposure to individuals with implants (e.g. cardiac pacemaker, etc.) (11). For example, some modern pacemakers switch into asynchronous mode at roughly 5–7 G, whereas some pumps may be affected only by far greater magnetic fields. Additional information is available at www.fda.gov.

Ferromagnetic surgical tools and devices are not affected until much greater field strength. Many iMRI sites mark lines on the floor to indicate an area where non-MRI safe tools can be safely used and no attraction or torque (alignment of a ferrous object with the magnetic field) are observed (Figures 3 and 4). No strict criteria exist at the time of this publication to indicate exactly at what strength the line should be drawn. Magnets with active shielding exhibit a very low fringe field far from the iso-center, with a dramatic increase in field strength within feet of the opening of the bore. This sudden change in

Table I. Possible MRI configurations for intraoperative or interventional imaging.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Field (Tesla)</th>
<th>Bore length and diameter</th>
<th>Access to patient</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long bore (closed)</td>
<td>1–3 T</td>
<td>200–300 cm length 60 cm diameter</td>
<td>Poor but not impossible</td>
<td>Highest image quality</td>
</tr>
<tr>
<td>Short bore (closed)</td>
<td>1.0 – 1.5 T</td>
<td>125 cm length 70 cm diameter*</td>
<td>Limited but not poor</td>
<td>Fast Gradients/cardiac/vascular applications</td>
</tr>
<tr>
<td>Horizontal open gap</td>
<td>0.2 – 1.0 T</td>
<td>Height 45 – 70 cm</td>
<td>Good access, but limited in vertical direction</td>
<td>Safety and instrument compatibility</td>
</tr>
<tr>
<td>Vertical open gap</td>
<td>0.5 T</td>
<td>Height approx. 70 cm Partially limited, width 56 cm</td>
<td>Good access but not fully unlimited</td>
<td>Intraoperative imaging, flexible positioning</td>
</tr>
</tbody>
</table>

*Note: With this particular design, the distance to the isocentre is 62.5 cm from the bore entrance and the gap from the patient table to the bore top is 55.5 cm.
Attraction gives little warning to a staff member holding a ferrous object as he approaches the magnet (13). Attraction and torques constitute the greatest risks in MRI. An object may become a projectile as it accelerates in the direction of the spatial gradients of the static magnetic field. Large objects can generate incredible force as they are drawn into the magnet.

Currently, various MR systems used for diagnostic or research purposes operate with static magnetic fields that range from 0.064–8.0 Tesla. At the time of this publication, field strengths from 0.12T to 3T are used for iMRI.

Most ex vivo tests to determine MR safety or MR compatibility for implants and devices were performed at static magnetic fields of 1.5 Tesla or lower (14). This could be problematic for a patient with implanted devices exposed to a higher static magnetic field such as 3-Tesla units. Inside the human body, torque and attraction can cause an implant to tear surrounding tissue (11). Tearing and pain is most likely to be experienced in the strongest part of the gradient field, while the patient approaches the scanner before actually being placed within the bore.

Questions of how soon a patient may be safely scanned after surgery often arise. Patients with metallic “passive” implants (i.e. there is no power associated with the operation of the object), made from nonferromagnetic material (e.g. nitinol, titanium, elgiloy, tantalum, etc.) may undergo an MR procedure immediately after placement of the object using an MR system operating at 1.5 Tesla or less (12,14).

Table II. Operational Safety Rules should implement the following security and safety guidelines:

- All personnel must be trained and frequently updated on MRI safety.
- Access to the MR scanner room (high-magnetic-field area) is limited to trained personnel, screened patients or visitors accompanied by trained personnel.
- Entrance to the MR scanner room is controlled by a lockable door, and keys to the area are issued only to trained personnel.
- All entrances to the MR scanner room are visible to the system operator.
- All visitors are screened by the operator before entry.
- Appropriate warning signs must be posted.

Optional use of a scanner for ferromagnetic objects should be considered.
For objects that are weakly magnetic (typically certain types of coils, filters, stents and vessel occluders), a waiting period of 6–8 weeks prior to a MR procedure is recommended. In this case, tissue growth, scarring or granulation provides retentive or counter forces to prevent the object from hazardous movement within a field strength of 1.5 Tesla or less. Implants that are weakly magnetic but are rigidly fixed in the body, such as a bone screw, may be studied immediately after surgery (12). If there is any concern about the integrity of tissue with respect to its ability to retain the object in place during a MR procedure, the patient should not be exposed to the MR environment (14).

Emergency response

Nursing, anesthesia, MRI technologists, and operating physicians should be trained to respond to cardiopulmonary emergencies in the scanner room. Since MR-compatible equipment to resuscitate a patient does not exist, the patient should be brought to a safe area away from the scanner room.

Designated personnel should be responsible for maintaining access restrictions while other personnel expeditiously move the patient to the location where resuscitation will be performed. If it is impractical to remove the patient from the scanner room, and life saving equipment must be brought in, the magnetic field can be eliminated (run down). However, it is costly and time intensive to restore the magnetic field.

In case of sudden loss of magnetic field (quench), the cryogens that cool the magnet expand as they turn to gas and may escape into the room. It is prudent to vacate the room in case oxygen has been displaced, even if oxygen monitors read normal levels. The oxygen used in the OR setting as well as therapeutic heat sources (e.g., laser) result in a risk of fire. Non-ferrous fire extinguishers are available for the management of small fires. Sites should have a plan for rapid removal of patients in these life-threatening situations, even when there is no time to close a surgical wound. Policy and education should exist to prevent responders from other areas from bringing ferrous materials into the scanner room.

Acoustic noise

Care should be taken to protect the patient’s hearing, especially when under general anesthesia. The sound pressure level of a gradient coil impacting its mounting structure during scanning can exceed the occupational limit of 100 dB (root mean square). Hearing protection is mandatory in these cases (11,12,15). Interventional staff within the scanner room should also wear hearing protection (e.g.
noise-abatement headphones or earplugs), particularly if repeated imaging is necessary during a surgical procedure. Non-essential staff should be allowed to exit the room during scanning.

Time Varying Magnetic Field Exposure

In order to establish an allowable RF energy deposition, the Specific Absorption Rate (SAR), expressed in units of watts per kilogram of body weight, is based on levels that induce a maximum change in tissue temperature of 1°C. According to specific criteria, the SAR must be no greater than 4 W/kg averaged over the whole body for any 15-minute period (15). The European Directive (ED) however, sets the exposure limit values for whole body average SAR to be as low as 0.4 W/kg. These limits are far below those which may produce known short-term negative health effects, following the definition of the World Health Organization (16).

In the areas of tissue in contact with surgical tools or conductive wires (e.g., for ECG, EEG, temperature measurement, cautery or radiofrequency grounding pads, etc.), induced currents can be large enough to cause significant burn (11). Care must be taken that conductive wires, thoroughly tested and determined MR compatible, do not overlap or form loops, run in parallel as close to the center of the magnet bore as possible, and are insulated from contact with conductive materials or bare skin, in particular in patients with conductive materials applied to the skin (such as tattoos, eyeliner, or some cosmetics). The maximum induction occurs with the plane of a loop perpendicular to the changing magnetic field, therefore surface coils need to be insulated from the patient’s skin (11). In any case patients should be informed of the possibility of heat sensation (that usually occurs within the first 20–60 seconds).

Again, cables should be padded to eliminate contact with the skin or, if possible, removed during scanning. As a preventive measure a cold water compress or ice packs can be applied to sites subject to heating, such as RF electrode pads. Skin-to-skin contact points should be avoided, since they have been reported to cause burns as well (17). These precautions are of particular importance in patients under sedation or general anesthesia who are unable to notice or report pain.

Occupational considerations

Several attempts have been made to provide regulatory guidelines for the chronic exposure of personnel required to work near strong magnetic fields. An example is the guideline proposed by the National Radiological Protection Board of the United Kingdom, that customarily takes the form of limits over a course of an 8-hour working day. In this guideline, a worker could be in a 0.2-T field for the entire working day, whereas in a field of 1.6 T exposure should be restricted to one hour (18,19). If only extremities are exposed to the field, a higher average field (2T/day) is permitted (20).

In a new European Directive (ED), accepted in 2004, new electromagnetic field (EMF) exposure limits for workers in general are defined in the 0 – 300 GHz frequency range. The ED requires mandatory adoption into national law for each EC country within four years, i.e. by 2008. The new ED follows the proposed guidelines from the International Commission on Non-Ionizing Radiation Protection (ICNIRP) that lists conservative low exposure limits and does not include a risk versus benefit analysis of the acceptability of practices that lead to EMF exposure above these limits. Although the limit values for the static magnetic field were excluded, the ED still includes the ICNIRP limits for RF power and gradient power, so that it may indeed become a limiting factor for the clinical MR practice (20–30). Although the underlying assumptions are currently under question and great scrutiny, these restrictions will severely limit interventional practice in the EU (23). In any case, the MR user should be aware that even well-known SAR exposure limit values do not warrant a “healthy environment”. Recently, experiments have indicated that the proposed SAR exposure limit values (10 mAm^2), defined in terms of induced current density to the head or trunk, would be exceeded by a worker standing within 130 cm of the isocenter (31). Also, the exposure of staff to peak magnitude of the magnetic flux density exceeds the limits up to a distance of 180 cm from the isocenter. The exposure is expected to increase for modern short bore systems with higher-powered gradients. To minimize the SAR exposure efforts are underway to use combinations of gradient axes, using real pulse sequences and modern short bore MR systems (11,12,15).

MR-compatibility testing

Devices not marked as MR-compatible by a vendor need to undergo meticulous testing before being used in a MR environment. Any and all devices that are or may contain metallic components that are to be brought into Zones 3 or 4 should be positively identified or tested for ferromagnetic properties prior to their being granted access to these regions.
Devices screened for safe access to Zone 3 or Zone 4 must be labeled with green “MR Compatible” labels or red “Not MR Compatible” labels. “MR-conditional” is used for all other devices in which testing conditions would be specified—for example, “MR-tested for up to x static magnetic field and up to y static spatial gradient field” (32). Testing with a powerful handheld magnet (≥ 1000 G recommended) can be performed to detect if an object is not safe. Other tests such as magnetic force and torque tests can be employed, but need careful setup of the tests and supporting gear such as rope brakes, scales, etc. to avoid harm to the operator and damage to the MR scanner (33,34). Electronic devices used in the MR suite need to pass a series of tests before they enter into regular preventive maintenance schedule (4). Further tests include signal-to-noise ratio and homogeneity tests while the device is operating and exposed to various MR scanner modes. This topic is expanded in this special edition.

**Anesthesia management for MR imaging**

The iMRI environment is the most challenging setting for out of OR anesthesia. In general, off-the-shelf equipment, familiar to all staff anesthesiologists, cannot be used. Access and line of site to the patient is limited when the patient is inside the bore of the scanner. ECG lead placement necessitated to achieve a clean trace in the MRI, prohibits true Lead I,II and III waveforms (35). Moreover, waveforms are distorted by the effects of the magnetic field and are subject to induced noise during scanning.

As blood, an electrical conductor, jets through the aortic arch in the presence of an external magnetic field, a voltage is induced at the skin surface. This so called magnetohydrodynamic effect masks S-T segment changes, which is an indication of cardiac ischemia (36). Thus all patients should be carefully screened for risk of ischemia before being consented for a procedure in the iMRI area. Anesthesia staff must be prepared to face problems involved with moving a patient large distances as more modalities are used in conjunction with MRI to guide a procedure (29). MRI-compatible anesthesia equipment is commercially available from several manufacturers, and general anesthesia services have been established in many MRI centers worldwide (37). Further guidelines have been established by the American College of Radiology, the American Society of Anesthesiology and the Joint Commission on Accreditation of Healthcare Organizations and publications (4). Guidelines request two sources of oxygen (preferably central source piped oxygen and a backup full E cylinder), suctions, an anesthesia machine if administering volatile anesthetics, a scavenging system for waste anesthetic gases, a self-inflating hand resuscitator bag able to deliver 90% oxygen and positive pressure ventilation, standard of care monitors and equipment, sufficient electrical outlets, and illumination. Mason recommended that it is safer to position stocks for essential medications, alternative airway devices, intravenous supplies, endotracheal tubes (ETT), suction catheters, syringes and needles on a non-MR compatible cart outside the scanner and to bring only the “essentials” into the suite, arranging them on the anesthesia machine (38). Laryngoscope handles and blades are generally non-ferrous but require lithium batteries. Beware that some batteries labeled as “lithium” MRI may be tainted with a ferrous-containing substance (38). Despite being MRI compatible, personal experience has demonstrated that the power source for MR-compatible anesthesia machines may cause image artifacts if left in the scanner (38).

**Safety via development**

**MR-compatible instruments and surgical devices**

Owing to the relatively high magnetic fields applied in magnetic resonance scanners, standard medical-grade stainless steel surgical instruments cannot be used in these systems. Such instruments, with paramagnetic or ferromagnetic content, cause disturbing image artifacts owing to magnetic field inhomogeneities that are created by the susceptibility mismatch between tissue and the instrument. In addition, these materials are subject to torque and displacement in the magnetic field and may become a projectile. Previous reports have shown that titanium, titanium alloy, ceramic materials and others cause relatively small artifacts that are the direct result of the very low magnetic susceptibilities (39). These materials have been identified to be safe for use in an MRI environment (40), but may exhibit artifacts at higher fields.

Passive visualization techniques take advantage of some residual device-induced susceptibility artifacts, generally sufficient for biopsy and drainage procedures. It is also a well-known phenomenon that artifacts related to the use of the T1-weighted, spin echo pulse sequences are smaller than those seen with the GRE pulse sequence. Fortunately, there are pulse sequences (e.g., fast spin echo) and other techniques (swapping phase and frequency) that can be used to minimize artifacts associated with the presence of metallic implants (41). For intravascular interventional procedures, active tracking techniques...
are under development, integrated into devices such as catheters and endoscopes (7,42).

Pulse sequences

Pulse sequences for guidance of interventional procedures have to be tailored to the interventional or surgical procedures (1,9). Procedures that require relatively high tissue contrast (T2 weighting) but only limited temporal resolution can be monitored with Fast Spin Echo (FSE) techniques, which allow image acquisition in approximately ten seconds. Sequences that provide higher temporal resolution do so at the cost of spatial and contrast resolution. These sequences include multiple gradient echo techniques with an acquisition time typically in the range of few seconds. Advancements in the last decade have made it possible to acquire and display more than ten images per second in real-time with millimeter resolution in all three directions. This temporal and spatial resolution is considered high enough to guide most interventions (13,43). High-resolution images, made possible by the advent of multichannel receiver systems, improved graphics, higher processor speeds, and increased in speed and quantity of memory can be used to update pulse sequence parameters in real-time, thereby opening new opportunities for interventional MR imaging that extend from biopsy and thermal therapy to image-guided vascular and cardiac procedures. However, RF heating of wires used for device localization and the noise generated by rapid switching of MR gradients constitute significant obstacles yet to overcome. It is anticipated that these topics will emerge as critical concepts in the next decade of interventional MR imaging research (13).

Interactive imaging and real-time guidance

The principles of interactive-image guidance, frameless stereotaxy, and navigation were established in neurosurgery, where preoperative images were used. Optical tracking devices integrated within the MR scanner combine surgical navigation with nearly real-time imaging and do not require a registration process between the patient and the images because images are acquired in the surgical position of the patient (9). Thus, coordinates of the optical tracker can be used to control the scan plane of the nearly real-time imaging (Figure 6) and to display a virtual instrument (e.g., biopsy needle or therapy probe) and its trajectory, overlaid on the MR image (1,44). Interactive, near real-time imaging can be accomplished by positioning an optically tracked handpiece to determine an appropriate trajectory in three planes. Once a trajectory is chosen, a burr hole or craniotomy is drilled in the skull overlying the entry site. The ideal approach to a lesion is determined by using a combination of the nearly real-time imaging and conventional serial-volume imaging (Figure 7). During brain surgery, the operator can thereby successfully avoid vital vascular structures and critical brain regions. Currently, more than 2000 craniotomies with MRI guidance have been performed worldwide (4,9,44) without significant complications. MR was in particular helpful in a case of residual enhancing tumor that was visualized during surgery and further resected. Serial intraoperative imaging also clearly demonstrated that there are substantial shifts and deformations during surgery, caused by CSF drainage, tissue removal, and tissue reaction (swelling) to the manipulations (45). Furthermore, intraoperative, interactive MR-guidance has been shown to enable the detection of intra procedural complications such as hemorrhage (10,46).

Conclusion

The potential for injury or death in the MRI environment (2) should not be underestimated. Experiments and reported accidents show the environment contains potential risk (47). However, the authors of this work have collectively performed over 2000 cases without serious adverse incident, at their two centers, over a twelve-year period using 0.2T and 0.5T scanners. Hill reported a similar four-year experience using a 1.5T MR system together with a cardiac c-arm x-ray system for MR guided cardiac catheterisation (48). Hushek et al reported another perfect safety record over more than five years with more than 400 surgeries being performed at 0.5T (4). These examples give promise that the iMRI environment can be safe.

Safe behavior can be engrained into personnel by training and policy enforcement. Safe behavior can be coerced by measures such as suite layout and restriction of access. These two means must act in concert to ensure safety.

We echo the recommendation (29) of a gradual progression in establishing an iMRI suite. The right team members, well thought-out architectural planning, and proper policy and training are an essential start. Human vigilance and enforcement of policy must be ongoing. For any new procedure, a dry run should be executed to identify the potential pitfalls. A small core staff should be involved in the first cases. We recommend video taping and reviewing the procedure. Some architectural firms or external centers will provide a safety survey at this stage. In expanding the services, the experienced core staff should train new staff members. To streamline
cases, time stamps of each portion of the procedure should be recorded. Analysis and optimization processes to maximize case efficiency can be applied. The less time a patient is in the iMRI environment, the less time he and the staff are at risk.

As the field of iMRI evolves, magnetic field strengths will grow, gradients and thus potential for heating will increase, and the armamentarium of interventional devices used will expand. As these advancements happen, risk will increase. We must be prepared to face these risks with increased vigilance, advances in materials from which instruments are made, and advances in scanner software that can achieve fast imaging without excessive exposure.

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References


Figure 7. Intraoperative image-guidance during craniotomy of a brain tumor (meningioma). (a) T2-weighted magnetic resonance (MR) images were acquired within the Signa SP, preoperatively. Localization of the best entry site for craniotomy was accomplished by visualization of the surgeon's finger in the MR images. (b) T2-weighted MR images show the resection cavity, partially filled with liquor. (c) T1-weighted intraoperative MR image following contrast injection shows still some residual tumor at the resection margin. (d) T1-weighted intraoperative MR taken after complete resection shows no residual tumor.