INTERVENTIONAL AND INTRAOPERATIVE MAGNETIC RESONANCE IMAGING

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Key Words MRI, interventional MRI, minimally invasive therapy, image-guided therapy

Abstract The goal of the Image Guided Therapy Program, as the name implies, is to develop the use of imaging to guide minimally invasive therapy. The program combines interventional and intraoperative magnetic resonance imaging (MRI) with high-performance computing and novel therapeutic devices. In clinical practice the multidisciplinary program provides for the investigation of a wide range of interventional and surgical procedures. The Signa SP 0.5 T superconducting MRI system (GE Medical Systems, Milwaukee, WI) has a 56-cm-wide vertical gap, allowing access to the patient and permitting the execution of interactive MRI-guided procedures. This system is integrated with an optical tracking system and utilizes flexible surface coils and MRI-compatible displays to facilitate procedures. Images are obtained with routine pulse sequences. Nearly real-time imaging, with fast gradient-recalled echo sequences, may be acquired at a rate of one image every 1.5 s with interactive image plane selection. Since 1994, more than 800 of these procedures, including various percutaneous procedures and open surgeries, have been successfully performed at Brigham and Women’s Hospital (Boston, MA).

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INTRODUCTION

With the increasing use of minimally invasive procedures, there is a strong demand for imaging techniques that can be used to visualize anatomy, interventional or surgical devices, and therapeutic effects. To date, ultrasound, fluoroscopy, and computed tomography have been the preferred modalities for image guidance of percutaneous interventional procedures and for some surgeries. Although each of these imaging techniques offers some specific advantages and drawbacks, their utility is limited (Table 1).

Magnetic resonance (MR) imaging (MRI) offers excellent soft-tissue discrimination, which can be enhanced with specific contrast agents, multiplanar imaging, and a high spatial and temporal resolution. Blood vessels can be reliably visualized either with contrast agents or by using the inherent sensitivity of MRI to flow. MRI parameters are also sensitive to temperature, and thermally induced phase transitions can be relatively easily recognized with MRI. Today, MRI has the greatest potential for monitoring interventional and surgical procedures, providing the impetus for the development of dedicated systems for MRI-guided therapy (1). These systems include percutaneous, endoscopic, open-surgical interventions, and various thermal ablations.

INTERVENTIONAL MRI DESIGN FEATURES

The ideal interventional MRI unit allows almost unlimited direct access to the patient from all the sides, while enabling the operators to obtain high-resolution images in any desired plane nearly in real time. The system should emulate the advantages of other competing image guidance systems by providing multiplanar,
TABLE 1 Advantages and disadvantages of imaging methods

<table>
<thead>
<tr>
<th>Imaging method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasound</td>
<td>Commonly available</td>
<td>Lower spatial and contrast resolution</td>
</tr>
<tr>
<td></td>
<td>No radiation</td>
<td>Cannot be used in imaging of bone and air-filled spaces</td>
</tr>
<tr>
<td></td>
<td>Low cost</td>
<td>Limited use for thermal monitoring</td>
</tr>
<tr>
<td></td>
<td>Real-time imaging</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Easy access to the patient</td>
<td></td>
</tr>
<tr>
<td>Fluoroscopy</td>
<td>Real-time imaging</td>
<td>Radiation</td>
</tr>
<tr>
<td></td>
<td>Bone imaging</td>
<td>No multiplanar imaging (projection)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Insufficient contrast resolution for soft tissues</td>
</tr>
<tr>
<td>Computed tomography</td>
<td>Excellent for bony structures</td>
<td>Radiation</td>
</tr>
<tr>
<td></td>
<td>Reliable geometrical visualization</td>
<td>Limited multiplanar visualization</td>
</tr>
<tr>
<td></td>
<td>Stereotactic procedures feasible</td>
<td>Limited soft-tissue contrast</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not sensitive to temperature</td>
</tr>
<tr>
<td>Magnetic resonance imaging (closed system)</td>
<td>Excellent soft-tissue contrast</td>
<td>Cost</td>
</tr>
<tr>
<td></td>
<td>Multiplanar imaging</td>
<td>No access to patient during imaging</td>
</tr>
<tr>
<td></td>
<td>Very sensitive to flow, diffusion and temperature</td>
<td></td>
</tr>
<tr>
<td>Magnetic resonance imaging (open system)</td>
<td>Access to patient during imaging</td>
<td>Availability</td>
</tr>
<tr>
<td></td>
<td>Nearly real-time imaging</td>
<td>Cost</td>
</tr>
<tr>
<td></td>
<td>Multiplanar imaging</td>
<td>Limited field strength</td>
</tr>
<tr>
<td></td>
<td>Adequate soft-tissue contrast</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sensitive to temperature</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No ionizing radiation</td>
<td></td>
</tr>
</tbody>
</table>

interactively generated, high-spatial- and temporal-resolution images. In addition, the same standards of sterility and patient monitoring must be met as those in conventional operating rooms. Full access to anesthesia, monitoring, and life-support equipment must be available (1, 2). Several scanner configurations are currently used for MRI-guided procedures. These include (a) modification of the conventional high-field (1.5-T), long-bore configuration; (b) high-field (1.5-T), short-bore design; (c) low-field (0.1- to 0.3-T) and midfield (0.5- to 1.0-T) horizontal-gap open configuration; and (d) vertical-gap, mid-field (0.5-T) open configuration. These scanners are summarized in Table 2.

Although the conventional closed, long-bore configuration systems provide the highest image quality, there is no direct intraprocedural patient access. However, this design is compatible with certain minimally invasive procedures, such as thermal ablations. Interstitial radio frequency (RF), laser, microwave, or cryoprobes
TABLE 2  Possible MRI configurations for interventional imaging

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Field</th>
<th>Access</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long bore (closed)</td>
<td>1–3 T</td>
<td>No</td>
<td>Highest image quality</td>
</tr>
<tr>
<td>Short bore (closed)</td>
<td>1.0–1.5 T</td>
<td>Poor</td>
<td>Fast gradients/cardiac/vascular applications</td>
</tr>
<tr>
<td>Horizontal open gap</td>
<td>0.02–0.6 T</td>
<td>Limited</td>
<td>Safety and instrument compatibility</td>
</tr>
<tr>
<td>Vertical open gap</td>
<td>0.5 T</td>
<td>Full</td>
<td>Intraoperative imaging; flexible positioning</td>
</tr>
</tbody>
</table>

can be positioned before sliding the patient into the bore of the scanner. The subsequent high-field MRI can be used to monitor the thermal-ablation therapy. Alternatively, thermal ablation can be performed without a probe by using a focused ultrasound system, which can be incorporated into the MRI scanner (3–5). The MRI-guided, focused ultrasound technique may be the ultimate minimally invasive therapy, as energy is delivered through the body surface and focused deeply, eliminating the need for insertion of any probe. The major disadvantage is the inability of ultrasound to penetrate gas-containing structures such as lung or bowel and the relative difficulty in transmitting acoustic energy through the bone.

The closed short-bore configuration with flanged bore openings permits slightly improved patient access and may be most useful for cardiac and vascular applications and for some percutaneous approaches. Miniature endovascular coils mounted on catheters permit tracking of the catheters as they are positioned within the vessels (6). Their position can be superimposed on flow-sensitive MR images, creating a “roadmap” type of catheter localization. In addition, endovascular coils enable imaging of the vessel walls for evaluation of plaque and of patient response to interventions such as angioplasty (7–11).

The horizontal open gap MRI design provides horizontal access to the patient, allowing most radiologic percutaneous procedures to be performed. The low field minimizes the need for shielding of equipment, but also potentially limits imaging capability. The overlying magnet structure precludes open surgical procedures while the patient is within the imaging field, but intraoperative imaging is possible by physically moving or swinging the table into and out of the MRI scanner to obtain images.

The Signa SP vertical-gap mid-field-strength MRI system was developed by General Electric Medical Systems (Milwaukee, WI) in collaboration with Brigham and Women’s Hospital (Boston, MA) in 1993. This design is the only one that permits true intraoperative MRI without moving the patient (Figure 1), with the exception of extremely low-field, permanent-magnet, open-configuration scanners. The Signa SP has been described in detail elsewhere (2, 12) and consists of two vertically oriented superconducting coils separated by a 56-cm gap, within which a 30-cm sphere of uniform static magnetic field is maintained for imaging. Because the superconducting material composing the magnet can be operated at a
INTERVENTIONAL & INTEROPERATIVE MRI

Figure 1 Clinical access and working zones within the Signa SP. Effective MR imaging is possible over a 30-cm-diameter spherical volume, at the center of the magnet.

higher temperature than those materials in conventional scanners, a gaseous helium cooling system is used, rather than a space-consuming, liquid-cryogen-based cooling system (Figure 2; see color insert). Since the first prototype of this scanner was installed at the Brigham and Women’s Hospital in 1993, 15 other Signa SP systems have been or will soon be installed worldwide.

Unlike the conventional RF coils, which limit patient access, specially designed flexible transmit/receive surface coils have been designed to be placed on the patient in close proximity to the imaging volume. Such coils do not interfere with surgical and interventional access (Figure 3; see color insert). After placement, the coil is covered with sterile drapes. Although these surface coils cannot provide uniform signal intensity of an entire cross-section of the abdomen, the quality of imaging is comparable with that of a conventional 0.5-T system.

The MRI system is maintained in an operating-room environment, with adjacent clean and scrub areas. The design of the intraoperative MRI interventional suite at Brigham and Women’s Hospital has been reported in detail (2, 12). It was necessary for vendors to design or modify devices, such as anesthesia machines, anesthesia monitors, ultrasonic aspirators, surgical microscopes, and pneumatic neurosurgical drills, so that they are compatible with the MRI environment. Other devices, such as monopolar and bipolar electrosurgical units, cortical stimulators, RF lesion generators, and headlights, are used with long cables to ensure that the sources remain in a low-field area of the room. Other devices, such as lasers, cryotherapy systems, and hot-air patient warmers, remain outside the room. All
Figure 2  The GE Signa SP 0.5 T MRI is designed for both interventional and intraoperative procedures. Constructed by two interconnected cryostats separated by a 56-cm gap, the Sigma SP permits access to the patient during imaging. Depending on the procedure, the patient table may be positioned coaxially or perpendicularly to the axis of the scanner. MR-compatible anesthesia equipment and MR-compatible instruments can be placed nearby. LCD screens to monitor imaging data during a procedure are mounted on both sides of the work area at eye level. (Courtesy of Gary Zientara, Ph.D., Department of Radiology, Brigham and Woman’s Hospital, Boston MA.)
Figure 3  A view from the surgeon’s position inside the Signa SP magnetic resonance imaging system. In neuro-surgical procedures the patient’s head is fixed with an MR-compatible Mayfield clamp. After the appropriate entry point is selected by MR imaging, the skin site is marked. Sterile drapes are placed over the flexible surface coil when the sterile surgical field is being prepared.
hand-held instruments must be nonparamagnetic. Those instruments that remain in situ during imaging must be constructed from materials that do not cause susceptibility artifacts in the images.

The environment of the MRI system permits it to be used for both interventional and intraoperative applications. Although open surgery is, by definition, not a minimally invasive procedure, intraoperative image guidance can, in combination with accurate targeting and surgical planning, minimize the damage to healthy tissue and maximize removal of the abnormality. In the remainder of this paper, we summarize our experience with MRI-guided interventional and intraoperative procedures, using the Signa SP.

Anesthesia Considerations

MRI-compatible anesthesia equipment is now commercially available from several manufacturers (13), and general anesthesia services have been established in many MRI centers worldwide (14). Risk of burns from interactions of the scanner with electrocardiograph (ECG) leads is significantly lower than with conventional high-field scanners, as reported by Keens & Laurence (15). Limitations in monitoring ECG, however, remain a problem; it is difficult to achieve true lead I, II, and III waveforms owing to the close placement of the electrodes that is necessitated by their use in the magnetic field. Furthermore, the magnetohydrodynamic effect of blood flowing through the heart creates an ECG artifact, masking indications of ischemia (17).

Pulse Sequences

Pulse sequences for guidance of interventional procedures have to be tailored to the interventional or surgical procedures. 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 \( \sim 10 \) s.

Sequences that provide higher temporal resolution do so at the cost of spatial and contrast resolution. These sequences include multiple gradient echo techniques. The acquisition time for these sequences is typically in the range of few seconds. In the future there will be a substantial role for limited k-space sampling methods and for dynamic, adaptive-imaging sequences (18–20).

Interventional 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. Some standard instruments are potential projectiles, possibly endangering both
the patient and the operators. Therefore, several alloys and ceramic materials have been identified that may be safely used in an MRI environment. Certain alloys have been developed to minimize image artifacts (21–25).

Passive visualization techniques take advantage of some residual device-induced susceptibility artifacts. The visualization is generally sufficient for biopsy and drainage procedures. Passive visibility of these devices has been investigated at different field strengths. For intravascular interventional procedures, active tracking techniques are under development. Miniature RF coils can be integrated into devices such as catheters and endoscopes. The position of these minicoils can then be localized with MRI in all three dimensions and nearly in real time (26).

INTERACTIVE IMAGING AND REAL-TIME GUIDANCE

Interactive imaging requires navigational tools. The principles of interactive-image guidance, frameless stereotaxy, and navigation were established in neurosurgery, in which preoperative images were utilized. The Signa SP combines surgical navigation with nearly real-time imaging. Unlike procedures in the conventional operating room, a registration process between the patient and the images is not necessary, because images are acquired in the surgical position of the patient.

An optical tracking device (Flashpoint 5000, Image Guided Technologies, Inc, Boulder, CO) is integrated into the Signa SP. Three high-resolution charge-coupled device video cameras located above the magnet’s isocenter detect the emissions of light-emitting diodes (LEDs) on a hand-held interactive probe. A dedicated computer digitizes the position of each LED. Specialized image guidance software implemented on an interactive workstation (Sun Microsystems, Mountain View, CA) uses these coordinates to control the scan plane of the nearly real-time imaging (Figure 4; see color insert). The workstation is capable of displaying a virtual instrument (e.g. biopsy needle or therapy probe) and its trajectory, overlaid on the image.

The accuracy of the navigation system has been strictly calibrated and maintained within the working space, with a resolution of 1 mm. Interactive, nearly real-time imaging is accomplished by positioning an optically tracked hand piece 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. During brain surgery, the operator can thereby successfully avoid vital vascular structures and critical brain regions.

Depending on the MRI sequence selected, continuous scanning provides updated MR images every 2–20 s. Graphic annotation allows visualization of the “virtual needle” for trajectory planning. The “fast needle graphics” feature allows the user to make fine adjustments to the virtual needle trajectory, which is displayed in real time, between image acquisitions. These features facilitate the feedback loop between the interventionalist or surgeon and the MRI system.
Figure 4  (a) The infrared light-emitting diodes (LEDs) on the handheld tracking device are registered by charge-coupled device (CCD) cameras mounted above the image volume. The position of the probe is calculated, and images can be acquired in a so-called “in-plane 0”, “in-plane 90” (the image plane is rotated along the probe’s axis), and in “perpendicular” to the probe. (b) The handheld tracking probe has LEDs located at the ends of the arms of the device. The probe is used to establish both the plane of imaging and the proposed trajectory of a needle placed through the center (arrow) of the device.
Interactive MRI can be used in several ways for planning and performing interventional and surgical procedures. For interactive imaging, the physician uses the interactive probes to navigate through the region of interest, in a manner similar to ultrasonography. Imaging planes can be obtained along the plane of the biopsy needle (or interventional probe) or perpendicular to the needle axis (27, 28). This technique is particularly useful for establishing the relationship between surface landmarks and underlying structures and planning the interventional or surgical approach. For targeting, the interactive probe is held stationary. Specific annotation is added to the acquired images. The trajectory and target can then be verified by imaging in three orthogonal planes. When the desired trajectory and target point have been established, the interventional probe can be advanced, and its progress can be observed on the MR images as they are acquired in nearly real time and that confirm satisfactory positioning of the biopsy needle or therapeutic probe (Figure 5).

To provide interactive information to the interventional radiologist or surgeon, a color liquid crystal display (LCD) screen is mounted on each side of the Signa SP at eye level. These screens can be used to display images directly from the MRI scanner, or they can display the nearly real-time images to the physician as they are acquired (Figure 2; see color insert).

CLINICAL EXPERIENCE

Since 1994, >2000 interventional or surgical procedures have been performed in the Signa SP system at 11 sites worldwide. Most of them have been minimally invasive procedures (Table 3). Other manufactures developed open and short-cylinder MR-systems so far to be used for perioperative imaging or to provide access during interventional procedures (Table 4).

<table>
<thead>
<tr>
<th>Procedure type</th>
<th>Total number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surgical</td>
<td>1045</td>
</tr>
<tr>
<td>Biopsy</td>
<td>555</td>
</tr>
<tr>
<td>Thermal ablation</td>
<td>378</td>
</tr>
<tr>
<td>Interventional</td>
<td>321</td>
</tr>
<tr>
<td>Kinematic studies</td>
<td>1414</td>
</tr>
<tr>
<td>Diagnostic imaging</td>
<td>3923</td>
</tr>
<tr>
<td>Animal studies</td>
<td>169</td>
</tr>
<tr>
<td>Total</td>
<td>7805</td>
</tr>
</tbody>
</table>
**TABLE 4**

<table>
<thead>
<tr>
<th>System Vendor</th>
<th>Field-strength</th>
<th>Type of magnet</th>
<th>Access</th>
<th>Patient aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Magnetom Open</em></td>
<td>0.2 T</td>
<td>Resistive</td>
<td>Horizontal</td>
<td>44 cm</td>
</tr>
<tr>
<td><em>Siemens AG</em></td>
<td>0.23 T</td>
<td>Resistive</td>
<td>Horizontal</td>
<td>46 cm</td>
</tr>
<tr>
<td><em>Outlook</em></td>
<td>0.2 T</td>
<td>Resistive</td>
<td>Horizontal</td>
<td>44 cm</td>
</tr>
<tr>
<td><em>Picker-Nordstar</em></td>
<td>0.3 T</td>
<td>Permanent</td>
<td>Horizontal</td>
<td>50 cm</td>
</tr>
<tr>
<td><em>Airis</em></td>
<td>0.35 T</td>
<td>Resistive</td>
<td>Horizontal</td>
<td>48 cm</td>
</tr>
<tr>
<td><em>Hitachi</em></td>
<td>0.35 T</td>
<td>Superconductive (cryogenless)</td>
<td>Horizontal</td>
<td>55 cm</td>
</tr>
<tr>
<td><em>Quad 7000</em></td>
<td>0.35 T</td>
<td>Superconductive magnet</td>
<td>Axial (limited)</td>
<td>60 cm</td>
</tr>
<tr>
<td><em>Fonar</em></td>
<td>0.35 T</td>
<td>Superconductive magnet</td>
<td>Axial (limited)</td>
<td>60 cm</td>
</tr>
<tr>
<td><em>SIGNA SP</em></td>
<td>0.5 T</td>
<td>Superconductive (cryogenless)</td>
<td>Vertical and axial (limited)</td>
<td>56 cm</td>
</tr>
<tr>
<td><em>General Electric</em></td>
<td>1.5 T</td>
<td>Superconductive magnet</td>
<td>Axial (limited)</td>
<td>60 cm</td>
</tr>
<tr>
<td><em>Philips</em></td>
<td>1.5 T</td>
<td>Superconductive magnet</td>
<td>Axial (limited)</td>
<td>60 cm</td>
</tr>
<tr>
<td><em>Symphony</em></td>
<td>1.0–1.5 T</td>
<td>Superconductive magnet</td>
<td>Axial (limited)</td>
<td>70 cm</td>
</tr>
</tbody>
</table>

**MRI-Guided Biopsy and Drainage Procedures**

When compared with ultrasound, computed tomography, and fluoroscopy, MRI guidance, at present, probably compares unfavorably in terms of procedure cost. This results primarily from the high initial capital investment for the installation of such a system. Nevertheless, some lesions are visualized only with MRI; MRI guidance is obviously the method of choice to biopsy those lesions that are difficult to access by standard imaging-guidance techniques.

**Brain Biopsies** For biopsies, the MR-compatible biopsy needle and tracking device are fixed to the flexible arm of an MR-compatible Bookwalter metallic arm (Codman, Boston, MA), which allows precise control of the needle as it is manipulated using nearly real-time imaging. Alternatively, an adjustable targeting device that fixes to the skull may be used (Navigus, Image-Guided Neurologics, Inc., Melbourne, FL; Neurogate, Daum BmbH, Schwerin, Germany; Snapper, Magnetic Visions GmbH, Ruti, Switzerland).
Figure 5  T1-weighted magnetic resonance images obtained during biopsy of an intracranial mass (glioblastoma), localized by using the interactive handheld tracking system with the integrated needle holder. (a,b) Parasagittal and axial images show the planned trajectory (dashed line) of the needle. (c) The biopsy needle itself as it is advanced into the lesion.

Contrast enhancing lesions, as revealed by high-field preprocedural imaging, may be biopsied under T1-weighted image guidance (7–10-s updates). Those lesions that are nonenhancing, after the injection of gadolinium-DTPA (dimeglumine penetrant), are biopsied by using T2-weighted FSE image guidance (14-s updates). Continuous imaging during biopsy procedures allows clinicians
to be certain of the location of the biopsy needle when specimens are taken, thus obviating the need for multiple needle passes and frozen-tissue sectioning.

The first MRI-guided brain biopsy was performed in January 1996, at our institution. In almost all patients undergoing brain biopsies that include interactive-MRI guidance, the procedure times are comparable to standard frame-based biopsies (27). In the mean time, >200 procedures have been successfully performed, including biopsy of lesions of the cortex, cerebellum, deep white matter, thalamus, basal ganglia, and brain stem. Currently, brain biopsies are performed by using the 3D Slicer, a software package that provides interactive navigation (discussed below). This system allows the easy definition of target and entry points and the selection of optimal needle trajectories. The 3D Slicer, used in conjunction with nearly real-time imaging and targeting devices, allows safe and effective biopsies to be performed.

To date, there have been no long-term complications noted in our patient population. In one patient undergoing biopsy, hemorrhage was noted in the operative site, which necessitated conversion to a craniotomy and removal of the clot; this case demonstrated the importance of immediate feedback on post-procedure complications, which would have been unavailable without the use of interactive MRI.

**Biopsies in the Head and Neck** One area where MRI-guided biopsies have been shown to be advantageous over computed tomography and ultrasound guidance is skull base lesions, in which beam hardening artifacts can make detection of lesions difficult and in which visualization by ultrasound is limited. MRI has been found to be an ideal imaging method because it provides the ability to freely choose an imaging plane and visualize blood vessels. Figure 5 illustrates an example of an intracranial biopsy performed with interactive MRI guidance. In this case, a tumor was localized in the pineal region, using FSE T2-weighted imaging. Initially, a trajectory was selected before the insertion of the biopsy needle, by positioning the biopsy guide equipped with optical tracking. A virtual needle with user-selectable lengths can then be displayed on the image to target the lesion. Once the trajectory is established, the needle can be advanced to the target and observed in nearly real time. Advancement is done in a stepwise manner as the needle approaches the target, an essential feature of frameless stereotaxy.

**Abdominal/Pelvic Biopsies** Abdominal/pelvic biopsies are performed in the MRI system in a manner similar to that using computed tomography or ultrasound guidance. The multiplanar imaging capability of MRI is particularly useful if a lesion is in the hepatic dome just below the diaphragm, which can be difficult to access with computed tomography or with ultrasound guidance (Figure 6). Some lesions are visible only on MRI, making it the guidance modality of choice. Real-time, interactive scan plane selection and trajectory planning in an Signa SP provided obvious progress from previous cross-sectional biopsy methods (28). Our experience with MRI-guided interventions involving the genitourinary system is described elsewhere (29).
Figure 6  Trajectory planning for MRI-guided needle biopsy of the liver, on the Signa SP magnetic resonance imaging system. The trajectory of the needle is predicted by the *dotted white line* superimposed on the image. The needle icon (*solid white line*) superimposed on the image during the intervention indicates the current location of the biopsy needle, determined by the optical-tracking system with LEDs (light-emitting-diodes) affixed to the biopsy needle holder. (Courtesy of Stuart G. Silverman, M.D., Department of Radiology, Brigham and Women’s Hospital, Boston, MA.)

**Breast Biopsies**  MRI of the breast is evolving as a useful modality in certain clinical situations. Occasionally lesions may be seen only on MRI but not with any other imaging method. Several guiding devices and breast immobilization techniques have been described to optimize MRI-guided breast interventions (30, 31). MRI can be used to place localization wires into tumors that are not visible with other modalities, before resection in the standard operating room (Figure 7). Recently, the Signa SP has been used to perform MRI-guided and excisional biopsy of breast lesions (32–34).

(a)  (b)

Figure 7  (a) Breast image acquired in the Signa SP magnetic resonance imaging system with an open-access breast coil. MRI was necessary because the tumor could not be seen on any other modality of imaging. (b) A localization wire placed under MRI guidance before lumpectomy was performed in the standard operating room.
Musculoskeletal Biopsies  The initial experience with MRI-guided musculoskeletal biopsies at the Brigham and Women’s Hospital has been published (28) and has been shown to be of benefit in the guidance of biopsies in patients with myopathies (35).

Drainage Procedures  As early as biopsies in MRI guidance were investigated (36), interest in drainage procedures was aroused. Early reports described clinical experiences with a wire-sheath system for biopsies and drainages (37, 38). Experience with MRI-guided catheter-based luminal interventions is experimental to date. However, the first case of a successful percutaneous nephrostomy tube placement in a patient in an interventional MRI system was reported by our group (39). Further experiences in performing an MRI-guided cholecystostomy (40), MRI-guided drainage, and shunting of brain cysts (41) were recently reported.

Functional Imaging

The unique design of the vertical gap allows patients to be imaged in sitting positions and allows joint movement without substantial limitations. MRI in a sitting position was also useful for functional imaging of the female pelvis floor, including those of patients with urinary stress incontinence and prolapse.

Functional Imaging of Spine  For dynamic and functional imaging of the spine, the patient’s upright sitting position is provided by an MR-compatible chair (Figure 1). In this study, the feasibility of obtaining functional MRI of the lumbar spine in an erect position and with flexion and extension was determined. Thirty subjects (including five normal volunteers) were imaged in a sitting position while performing flexion and extension. The alterations in posterior disc margin, size of neural foramina, and central canal were evaluated (42).

Although the foraminal size and posterior disc margins did not change appreciably from supine to upright positions, with extension, there was an increased bulge in 27% of discs (40% of those with desiccation). The central canal size (50%) and foraminal size (27%) decreased with extension, especially at levels with disc desiccation. Images obtained with the Signa SP were diagnostically adequate, although of inferior quality compared with those obtained with a conventional unit. Our preliminary results show the feasibility of obtaining diagnostic images of the erect lumbar spine with flexion and extension. The results are in agreement with those obtained from cadaveric studies. However, the utility of this method in diagnostic imaging of patients with low back pain remains to be determined.

Functional Imaging of Pelvis  To determine the anatomic differences in pelvic floor anatomy between continent women and women with stress incontinence, MRI in the supine and sitting positions in the Signa SP was used to assess whether these anatomic differences depend on the position of the subject during imaging.
T2-weighted images were obtained in the midline sagittal plane with subjects at rest and at maximal pelvic floor strain (5-s updates), by using a modified FSE sequence. In the axial plane, thin-section T2-weighted images were obtained with subjects at rest by using a standard FSE technique. Images were evaluated for mobility of the urethra and bladder neck and for integrity of the vagina, levator ani, and supporting fascia.

Pelvic floor laxity and abnormalities of the supporting fascia were more common in incontinent women than in continent women. Both descent of the bladder neck when subjects strained and the posterior urethrovesical angle were not significantly greater when subjects were measured in the sitting position (P < 0.1). Therefore, changes of pelvic floor laxity related to incontinence can be seen with subjects in both the supine and the sitting positions, but are increased in the sitting position (43, 44).

**Functional Imaging of Pediatric Hips**

To evaluate the use of the Signa SP during manual positioning of the hip in Legg-Calve-Perthes disease, Jaramillo et al have studied Legg-Calve-Perthes disease during manual positioning of the hip (45). Multipositional MRI and conventional arthrography were compared in the assessment of containment, femoroacetabular congruency, and femoral head deformity. While images of the hips in several positions were compared subjectively and objectively, MRI correlated well with arthrography for overall subjective assessment of severity of disease (r = 0.71; P = 0.01), with good interobserver agreement (κ = 0.65; P < 0.001). MRI images demonstrated all cases of hinge abduction shown arthrographically. However, MRI failed to depict one case of femoral head flattening, but correlated well with arthrography in the objective evaluation of joint fluid and lateral subluxation (r = 0.80; P < 0.01). In the evaluation of femoral head deformity, functional imaging did not perform as well.

**Functional Imaging of Patellofemoral Joints**

Imaging of patellofemoral joints with quadriceps loading is recommended because associated contracting muscles and related soft-tissue structures can be evaluated (2, 46–49). Therefore, the improved sensitivity obtained with the dynamic technique can eventually lead to better therapeutic and surgical outcomes in patients with patellofemoral pain. In the current study, we describe a new method for kinematic MRI of patellofemoral joints during active flexion and extension.

The subjects sit between two coils in the imaging chair with the knee supported at isocenter by a crossbar. The optical-tracking system (described above) was used to select the image slice plane and location interactively. This selection is of importance when imaging the patellofemoral joint, because a nonideal imaging plane may lead to misinterpretation of patellofemoral alignment (50).

Using a continuous fast-gradient-echo (FGR) sequence, kinematic studies may be performed by having the subject hold the joint in position for the duration of a single image, moving the joint during the subsequent image, and holding the new position for the next image. Because images are rapid (<1 s) and the image slice is
selected relative to the joint by the optical-tracking system, joint positioning can be controlled by muscular action rather than external devices. Resistance or weights may be applied to the limb being imaged. To assess the accuracy of the optical-tracking system in keeping the selected axial-imaging plane in the patellofemoral joints, we imaged the knee in three different flexion angles (45°, 25°, and 10°). At each knee position, an additional crossbar was placed under to the lower leg, just superior to the ankle. The flexion angle was confirmed with a goniometer. Either a circular coil with the extremity passing the coil or a flexible double loop coil, which was wrapped around the knee, was used.

The subject population comprised five asymptomatic volunteers (four males and one female). Nine knees (five right and four left knees) were imaged. At 45° extension, a coronal image was used to localize the sagittal plane, followed by a midpatellar sagittal image. With the optical-tracking probe affixed to the leg, an axial gradient echo (GE) image (1-s updates) was then acquired with nearly real-time imaging, through the middle of the patellar articular cartilage. The knee was passively moved to the next flexion angles, and axial imaging was repeated, maintaining the interactively chosen imaging plane.

These experiments demonstrate the potential of kinematic real-time imaging. We have shown still frames of a symptomatic subject with a provisional diagnosis of patellar malalignment (patellar lateralization). Furthermore, this new imaging method is an important step forward to more physiological imaging of joints. It will most likely improve the diagnostic accuracy in certain joint and spinal disorders. Although the imaging plane was not kept at exactly the same position, the 3-mm difference may be considered acceptable for qualitative evaluation of the patellofemoral motion. Improved diagnostic accuracy has a direct impact on patient care and surgical planning, eventually leading to improved quality of life and decreased health care costs.

Monitoring and Control of Magnetic Resonance Imaging-Guided Thermal Ablation

One of the greatest potentials of MRI is in monitoring the delivery of various destructive energies. Thermal monitoring is a particularly important application of interventional MRI. Thermal ablation techniques require not only good localization and targeting but also quantitative spatiotemporal control of energy deposition, which in turn requires monitoring of the thermal changes and the resulting tissue alterations (51–53).

Hyperthermia is based on slight temperature elevation (∼41°C), which requires relatively long homogenous thermal treatment of solid tumors. The main assumption of hyperthermia is that malignant cells have a higher sensitivity to thermal damage than normal ones. The temperature sensitivity of various MRI parameters (T1, diffusion, and chemical shift) can be exploited for detecting temperature changes within the critical temperature range. Compared with hyperthermia, thermal surgery uses temperatures that are >56–60°C, but for a short period only.
Above that temperature, proteins are denatured, and the resulting thermal coagulation causes irreversible tissue damage. Appropriate MRI sequences can demonstrate the normal margins surrounding thermal lesions, where the temperature elevation is still too low to cause cell necrosis, and, most importantly, can differentiate tissue phase transitions (54, 55).

**Laser Therapy** A typical high-temperature ablative procedure is interstitial laser therapy (ILT). This method can be direct continuation of a biopsy, because optical fibers can be introduced via a biopsy needle. Other alternative thermal treatments can be achieved with RF or microwave heating, which also require the insertion of a probe(s). The delivery of the laser energy to the target volume results in a coagulative necrosis. Based on our experience, we have developed computer-assisted, temperature-sensitive MRI for interstitial laser therapy (54–56).

Clinical applications involving tumor ablation in the brain and liver have already been initiated. The Signa SP imaging system was used to guide and monitor the accurate placement of the laser source (needle with optical fiber) at the targeted lesion. T1-weighted FSE and spoiled gradient-recalled echo sequence (SPGR) images, transferred to a research workstation from the MRI scanner, were used to reconstruct temperature mapping to monitor the effect of the laser ablation. Newly developed software in the imaging system and the research workstation enabled rapid (27–221-ms) and on-line temperature image reconstruction.

Because the T1 parameter is temperature dependent, simple subtraction of a baseline T1-weighted image from an image acquired during treatment can be calibrated to show the temperature of the treated tissue (Figure 8; see color insert). The temperature-dependent proton resonance frequency (PRF) shift is elucidated by a complex phase subtraction of SPGR images. Given that the temperature coefficient of tumor tissue in vivo is $\sim -0.01$ ppm/$^\circ$C, the relative temperature elevation during laser therapy can be measured. The results of temperature mapping were color coded and correlated to temperature in real time.

After the feasibility had been proven with animal experiments (51), several clinical applications of ILT in liver, brain, etc, have been published recently (52, 53). The preliminary study indicated that the presented system design is feasible for real-time and on-line monitoring of interstitial laser therapy (55, 56).

**Magnetic Resonance Imaging-Guided Cryotherapy** Cryotherapy is a freezing-based thermal method of ablation, which uses biopsy-like targeting as a first step before a cryoprobe is introduced into the tumor. The frozen tissue is clearly visible on MR images because the tissue water changes to solid ice crystals during the process. The solid ice crystals have an extremely short $T2/T2^*$ and give no measurable MRI signal with typical imaging techniques. The expanding freezing zone is therefore represented in MRI images by an increasing area of signal void.

Preliminary experiments done at Brigham and Women’s Hospital showed the feasibility to monitor cryotherapy in liver in real time with MRI (57). Recently, Silverman et al described a new method for cryoabrating tumors percutaneously,
Figure 8  Interstitial laser therapy of a brain tumor. (a) T1-weighted contrast-enhanced image acquired with a 1.5 T scanner before the procedure showed the enhanced brain tumor. (b) Thermal monitoring of interstitial Nd:YAG laser therapy with pixel-subtraction of T1-weighted fast spin echo images acquired within the Signa SP during a 4-W power deposition. Changes in signal intensity around the laser fiber were color-encoded to indicate thermal effect. (c) T1-weighted contrast-enhanced image at 1.5 T 24 h after laser treatment. Note the lack of enhancement within the tumor. The ring enhancement around the coagulated tumor is consistent with the breakdown of the blood-brain barrier. (Reproduced with permission of Mosby-Year Book, Inc., from: Jolesz FA, Kettenbach J, Hata N, Kikinis R, 1998. Image processing strategies for interventional MR. In Interventional MRI, ed. RB Lufking, pp. 171–86. St. Louis: Mosby).
Figure 9  Cryotherapy of liver metastasis. During freezing, magnetic resonance imaging was used to visualize the expanding, sharply marginated, teardrop-shaped iceball, which is seen as a signal void as it eclipsed the tumor.

using the Signa SP (58). With real-time frameless stereotactic guidance and repetitive multiplanar T1-weighted FSE or T1-weighted SE images, liver metastases were ablated during two freeze-thaw cycles (Figure 9). Dynamic scanning allowed the monitoring of the treatment progress as well as the avoidance of vital structures.

All procedures so far were performed successfully without significant complication. It was clearly demonstrated that percutaneous cryotherapy of liver metastasis is both feasible and safe. MRI depicts cryolesions as well-marginated signal voids, which can be clearly distinguished from untreated tumor intraprocedurally. These qualities maximize safety and chances for success.

**Magnetic Resonance Imaging-Guided Brachytherapy of Prostate**  Currently, interstitial $^{125}\text{I}$ implantation (brachytherapy) is a popular form of treatment for localized prostate cancer. This procedure is normally done under ultrasound guidance, with needles placed into the prostate through the perineum. With the Signa SP, it is possible to use MRI guidance to plan and perform the procedure. The use of MR images adds superior visualization of the prostate, its substructure, and surrounding tissues. This visualization is critical for treatment planning and guidance of the procedure.

The insertion of radioactive tissue-killing seeds via needles uses the same technology as probe-delivered thermal ablations. However, this procedure does not avail itself to real-time monitoring of tissue changes. On-line monitoring is replaced by real-time intraprocedural dose localization and planning capability. Intraoperative MRI-guided prostate brachytherapy has been introduced for selected patients with clinically localized prostate cancer. The goal has been to maximize the tissue destruction effect of the radioactive seeds and, at the same time, reduce the damage of adjacent normal structures (rectal mucosa, urethra, and neurovascular
bundle). By our hypothesis, this controlled-dose delivery will reduce the number of complications usually associated with this procedure under ultrasound guidance.

The prescribed minimum peripheral dose was 160 Gy to the clinical target volume, which was the MR-defined peripheral zone (PZ) of the prostate gland. By using the Signa SP, 5-mm image planes that were obtained throughout the prostate gland and the PZ of the prostate gland, anterior rectal wall, and prostatic urethra were identified on the T2-weighted axial images. After imaging, an optimized treatment plan for catheter insertion was generated intraoperatively. Each catheter containing the $^{125}\text{I}$ sources was placed under real-time MRI guidance to ensure that its position in the coronal, sagittal, and axial planes was in agreement with the planned trajectory (Figure 10; see color insert). Real-time dose-volume histogram analyses were used intraoperatively to optimize the dosimetry. All patients tolerated the procedure well, and a sufficiently high dose was applied to the clinical target volume within the prostate gland, whereas the anterior rectal wall received doses that were below the reported tolerance.

Real-time MRI-guided interstitial-radiation therapy provided the ability to achieve the planned optimized dose-volume histogram profiles of the clinical target volume and healthy juxtaposed structures intraoperatively, with minimal acute morbidity (59).

Magnetic Resonance-Assisted Surgical Procedures

One of the greatest promises of intraoperative MRI is for guidance during surgeries. The goal is to complement the surgeons’ visualization with volumetric imaging. Both open surgeries and minimally invasive endoscopic procedures provide views of the anatomy, which are limited to the surfaces beyond which only invasive cutting can penetrate. Interactive navigational guidance based on volumetric MRI can significantly complement this type of visualization. In addition, MRI can depict tumors better than direct visual inspection. Malignant brain tumors (gliomas) sometimes visually appear like normal brain tissue. Such lesions become visible only by MRI. This advantage can also be exploited by intraoperative MRI to detect margins and search for residual tumors.

Magnetic Resonance-Assisted Endoscopic Procedures

Using a nonmagnetic endoscope, our group reported initial results of sinus surgery, which was the first surgical application of interventional MRI in ear, nose, and throat surgery (60). Although sinus surgery is a common procedure, severe complications can be caused by the proximity of important anatomical structures to the paranasal sinuses. Image guidance was found to be helpful because MRI provided important adjuvant viewing beyond the limited perspective of the endoscope.

Magnetic Resonance-Guided Craniotomy

In neurosurgery the surgeon usually cannot see the tumor beyond the surface, so it is very helpful to have an imaging
Figure 10  Needle placement for MRI-guided prostate brachytherapy. (a) The patient is in the lithotomy position with a perineal template in place. There are two needles placed through the template, into the prostate gland. (b) Coronal fast-gradient-echo image shows the two needles in place. The left needle is slightly off target, as shown by the purple line. The purple line is based on the preplanned trajectory and position as prescribed by medical physicists. The needle may be repositioned, or the subsequent placements may be adapted, as mandated by the updated dosimetry planning.
modality to localize and target. For resections, the approach to the lesion is easily determined using the interactive near real-time system (Figure 4; see color insert).

After drilling a hole through the skull, the neurosurgeon performs an MRI-guided biopsy of a brain tumor with the biopsy needle attached to an optically tracked probe (Figure 5). With the availability of MR-compatible devices, including a high-speed drill and an intraoperative microscope, the first open brain surgery using intraoperative MRI was performed in 1996, at our institution. The first craniotomy was for the excision of a cavernous angioma. The first craniotomy for a brain tumor was the excision of a medial temporal ganglioglioma shortly thereafter. Currently, ~300 craniotomies with MRI guidance have been performed at our institution. Treated lesions include brain tumors, meningeomas, cavernomas, angiomas, and arteriovenous malformations (27, 62, 62).

To determine the margins of the tumor and to define enhancing, cystic, or necrotic parts during surgery, interactive, nearly real-time imaging is used. Combined with intraoperative, serially acquired MR images and interactive imaging with the optical-tracking system, the Signa SP is appropriate for surgery of deep lesions requiring biopsy, accurate stereotactic guidance, and/or resection.

In smaller lesions (e.g. small tumors or cavernous hemangiomas), accurate localization and targeting are obtained with interactive imaging. Once resection has begun, serial volume imaging is performed using fast T1-weighted spoiled gradient (SPGR) imaging or T2-weighted FSE images. The extent of resection can also be continuously evaluated. In many cases, tumor tissue that was inaccessible to direct viewing was seen on MR images and surgically removed under MRI guidance.

The surgeon may use the optically tracked probe or simply a finger to select the best entry site for the craniotomy (Figure 11). In another case during tumor resection, the residual enhancing tumor was visualized during surgery and further resected. Postsurgical high-field imaging, after edema was reduced, confirmed that no tumor remained.

**Magnetic Resonance Imaging-Guided Cyst Drainage**  For intracranial cysts, iso-osmotic gadolinium solution (0.02–0.5 cc of 0.5 mol/liter gadopentetate dimeglumine) can be instilled into the cyst to determine whether it communicates with the subarachnoid cerebrospinal fluid (CSF) space. Serial imaging was performed to elucidate the internal characteristics of the cyst and the rapidity with which CSF entered the subarachnoid cisterns. If the contents of the cyst were under pressure, a drain was placed within the cyst by the same approach used for the contrast agent injection. If free communication was demonstrated, no further intervention was performed. If no communication could be shown, the cyst was opened after craniotomy was performed. Gadolinium injection into extra-axial fluid collections differentiated free communication with the CSF space. The noncommunicating intracranial cyst and subdural collections were drained satisfactorily (41).

**Magnetic Resonance Imaging-Guided Pituitary Resection**  With the patients positioned in the Signa SP, 15 pituitary resections were performed. In all cases, the
Figure 11 Intraoperative image-guidance during craniotomy of a brain tumor (malignant glioma). (a) T2-weighted magnetic resonance (MR) images were acquired within the Signa SP, preoperatively. Localization for the best entry site for craniotomy was accomplished by visualization of the surgeon’s finger in the MR images. (b) This T1-weighted image was taken after the craniotomy. Localization was accomplished by the surgeon’s fingertip on the brain surface before tumor resection. T1-weighted MR images. (c) T1-weighted intraoperative MR image shows the resection cavity.

The tumor was satisfactorily removed. Serial sagittal, coronal, and axial T1-weighted images allowed the radiologist to direct the surgeon to the adenoma and avoid the cavernous sinuses and other parasellar regions [optical nerve (61; Figure 12)]. In several cases, residual suprasellar mass was detected by MRI, which was beyond the surgeon’s view through the exposed surgical site.

Magnetic Resonance Imaging-Guided Spine Surgery Intraoperative MRI guidance has also been applied for spinal surgery at Brigham and Women’s Hospital, since October 1996 (27). Since then, 14 procedures with a mean surgical time
of ∼3 h have been performed. These procedures include aspiration of cervical syrinx, anterior cervical discectomy with allograft interbody fusion and locking plate, cervical laminectomies and foraminotomies, and lumbar microdiscectomies.

Intraoperative MRI facilitates the procedures in several aspects. Initial imaging at the onset of the procedure is used to evaluate the position of the lesion in relation to the position of the patient’s head on the operating table. Real-time intraoperative MRI allows the surgeon to correct and optimize the approach during the surgical procedure. This imaging includes planning of the skin incision, craniotomy, and trajectory of the lesion through the brain parenchyma. Thus, surgical morbidity can be reduced by minimizing injury and maximizing preservation of normal brain tissue.

Furthermore, intraoperative, interactive MRI guidance has been shown to enable the detection of intraprocedural complications such as hemorrhage. It was also found to be superior to the eye (even if assisted by a microscope) in its ability to reveal abnormal tissue. The high sensitivity of MRI in the detection of brain lesions can be further enhanced by the intravenous application of gadolinium, which helps in evaluating the extent as well as completeness of removal of the lesion. Thus, the lesion margins and complete removal of the lesion are monitored with serial intraprocedural imaging. All of these features make the system highly superior to conventional (framed and frameless) stereotactic systems.
Magnetic Resonance Imaging-Guided Breast Lumpectomy

Breast lumpectomy is often accompanied by local recurrence. A negative surgical margin of the resected specimen is an important predictor of local control after breast conservation surgery (63). About 40%–70% of lumpectomy surgery results in inadequate surgical margins that require re-excision for adequate surgical treatment (64). Breast MRI with contrast agent has extremely high sensitivity in the detection of breast cancer; sensitivity of >90% has been reported (65). In recent reports, breast MRI shows the size of lesion and the extent of disease more accurately than mammography or ultrasonography (66). Lobular carcinoma and ductal carcinoma in situ (DCIS) are difficult to diagnose by conventional breast imaging. However, MRI accurately predicts the extent of these diseases (67).

MRI-guided lumpectomy allows delineation of the extent of disease in the patient’s position of operation. This procedure may reduce the frequent occurrence of positive surgical margin. Because permanent pathological results are not returned during surgery, MRI gives immediate feedback on residual tumor, before the surgical wound is closed. MRI-guided lumpectomy in the Signa SP may reduce or eliminate re-excision, owing to improvement in the ability to obtain negative surgical margins.

In an initial study, 11 patients (mean age, 54.9 years) underwent MRI-guided lumpectomy in the Signa SP for early breast cancer. We evaluated the feasibility of MRI-guided lumpectomy for breast cancer in the Signa SP. In all patients, indication of breast conservation therapy was confirmed. Days before MRI-guided lumpectomy, a core biopsy proved the presence of carcinoma. Diagnostic breast MRI was performed with a 1.5-T close-bore scanner (Signa Horizon, General Electric Medical Systems, Milwaukee, WI) on a separate day.

Axillary node dissection was performed outside the bore of the Signa SP, necessitated by the abduction of the arm for the surgical approach. The patient was then placed supine in the isocenter of the imaging volume of the scanner. The location and the extent of the breast lesion from preoperative images were confirmed by acquiring axial-gradient-echo three-point Dixon images. Because the three-point Dixon method is based on the relative phase difference between fat and water, it is thus not affected by absolute chemical-shift differences. The technique is therefore useful to achieve good fat-suppressed images even at 0.5 T (34, 69). In addition, axial three-dimensional fast-spoiled, gradient-recalled acquisition of the steady-state (3D FSPGR) images with the bolus injection of 20 ml of Gd-DTPA intravenously was obtained in all patients. After resection, this imaging was repeated with a second bolus of Gd-DTPA. When the contrast-enhanced area was seen in the lumpectomy site on postlumpectomy images, additional resection of the enhanced area was performed before the wound was closed.

All patients tolerated the procedure well, and there were no complications. Two false-positive cases from postresection images were noted. The resected cavity included air, which is known to yield a high-intensity susceptibility artifact at the interface of air and tissue. In one of these two cases, extensive atypical hyperplasia was pathologically present in additional resected specimens. Either of these causes
may account for the apparent enhancement. In the other case, the high intensity of fat was misdiagnosed as an enhanced area, because of lack of fat suppression in the 3D FSPGR images.

**Studying Brain Shift**

We have studied the behavior of the brain during surgery to develop models that simulate the brain’s biomechanical properties that are determined by the brain’s tissue properties, the internal chamber system, the external supporting structures, the arterial and venous mesh, and the pathology (70, 71).

Because both surgery and imaging take place within the Signa SP, the patient and the images are inherently registered. We performed repeated scanning to provide enough temporal resolution to uncover all phases of deformation. Scanning time and therefore image quality are limited by surgical demands. We found a sufficient compromise in routinely acquiring a volume scan of the brain, composed of 60 slices with 2.5-mm thickness (4-mm updates). The images were subsequently used for targeting the tumor and later post-processed for measuring brain shift.

Serial intraoperative imaging clearly demonstrates that there are substantial shifts and deformations during surgery, caused by CSF drainage, tissue removal, and tissue reaction (swelling) to the manipulations. At least two intracerebral compartments can be distinguished (brain surface and subsurface region) with distinct deformation patterns.

Intraoperative MRI surprisingly reveals that the midline cannot be relied on as a rigid landmark. After resection, the cortical displacement is 1.5 cm, but there is also a significant midline shift of ~1 cm. The left ventricle is compressed, and even the brain stem itself has shifted. The conclusions we can draw from these measurements are that the intraoperative distortions are not linear or homogenous, can affect the midline considerably, and will be difficult to predict.

**Augmenting Interventional Magnetic Resonance Imaging with the 3D-Slicer**

To amplify the benefits of interventional MRI, we have developed a method to fuse the multimodality preoperative images with intraoperative MRI and present these combined data during the MRI-guided surgery. This fusion augments the scanning component with computer software that maximizes the information available for the surgeons and increases the interactivity of an image-guided therapy system by focusing on the following five areas.

**Image Resolution** Some anatomical structures are difficult to distinguish on interventional MR images, but are clearer on conventional, diagnostic MRI that benefits from a higher magnetic field and longer applicable imaging times.

**Imaging Time** For surgical guidance to be interactive, images must be acquired quickly enough to be used without disrupting or slowing the procedure.
Fast imaging techniques are being developed, but, in general, faster imaging brings lower image quality. If images are displayed from a three-dimensional database, they can be presented much faster as real-time–acquired images. Therefore, neurosurgical guidance in our program primarily uses volumetric images (i.e. 3D FSPGR) and displays them with the 3D-Slicer intraoperatively. This database is updated with new images as frequently as is necessitated by brain shifts and deformations.

**Multimodal Fusion** Functional [e.g. function MRI (fMRI), magnetic resonance angiography (MRA), transcranial magnetic stimulation (TMS)] and metabolic data (e.g. magnetic resonance spectroscopy (MRS), SPECT, and PET) that are acquired preoperatively could deliver increased benefit if integrated with intraoperative anatomical information.

Integration of cortical mapping, fMRI, and SPECT and PET images will improve their effectiveness for intractable epilepsy cases or for tumor removal close to the primary motor or language cortex.

**Faster Localization** Interventional MRI provides the capability of planning approach trajectories by maneuvering a tracked wand and collecting images at the rate of 6–20 s per image. Although this is a significant accomplishment, an ideally interactive system needs an update rate of 10 frames/s.

**Three-Dimensional Visualization** Interventional images are presently two-dimensional, which requires the surgeon to mentally map the two-dimensional images seen on a computer screen to the three-dimensional operating field. The 3D-Slicer provides multiplanar and three-dimensional display options.

The 3D-Slicer is a software package that addresses the aforementioned areas (72). Therefore image resolution, imaging time, and localization are improved by performing real-time reslicing of both preoperative and intraoperative data sets and displaying them for simultaneous review. Multimodal information is incorporated through automatic registration, integrating imaging data from previous computed tomography or MRI along with functional physiologic data (e.g. TMS, MRA, and fMRI) and metabolic information (SPECT). These combined data can then be coregistered with intraoperative real-time MRI data. The resulting composite provides the surgeon with the most comprehensive view of the operative field and helps not only to plan, but also to execute the procedure. Coregistration of computed tomography, MRA, and MRI is especially helpful in skull base surgery. The combination of fMRI with cortical physiology is invaluable for executing surgical resection without sacrificing critical brain functions. SPECT registration to intraoperative MRI distinguishes metabolically active tumor parts from necrotic areas. Therefore, the 3D-Slicer features a computer graphics display that offers the flexibility to see the situation from viewpoints that are not physically possible.
DISCUSSION

Since its initial introduction, interventional and intraoperative MRI has evolved from a pure research tool into a technique that offers significant promise both in procedural ease and in added safety.

The addition of MRI guidance can greatly enhance the scope of current minimally invasive procedures by providing information about the relationship of the interventional device to the target lesion and the surrounding anatomic structures. The major advantages of MRI over other cross-sectional imaging modalities are the high tissue contrast, multiplanar imaging capability, and sensitivity to parameters such as temperature, which allows monitoring of therapeutic interventions during the treatment. The major disadvantages of MRI-guided interventions include the high cost of the imaging system and the high-magnetic-field environment, which complicate design of interventional devices and associated electronic equipment. Access to the patient for interventional procedures is a problem that has been solved to a large extent, but at this time no MRI system exists that combines the advantages of high field strength and open patient access. Interactive MRI is made available by navigational devices that control the plane of image acquisition and permit direct visual feedback to the interventionist or surgeon. This control allows nearly real-time control during the interventional procedure.

To meet the goals of cost-effectiveness, the system could be used for several procedures a day. The appropriate patient preparation areas, supplies, records staffing, and staff needs must be anticipated. In our program, the interventional MRI program is profitable and cost-effective. The numbers of cases and applications are constantly growing, and therefore a second system will be installed in the near future.

Despite its relatively high cost, MRI is unique in its capacity to enable the detection of subtle abnormalities and to actively monitor minimally invasive and thermal therapies (73). Apart from cost and practicality, the most important question is how to improve the patient’s outcome. There are a few measures to evaluate the usefulness of image-guided surgery, such as length of hospital stay, hospitalization cost, extent of tumor resection, postoperative functional status, symptom-free period, and survival period (74–77). Although a preliminary review of image-guided surgical cases is encouraging in this regard, a formal study that compares success rates of conventional neurosurgery and image-guided neurosurgery is still pending (78).

CONCLUSION

Intraoperative and interventional MRI was successfully implemented for a variety of surgical and minimally invasive percutaneous procedures. Interventional and intraoperative MRI provided continuous visual feedback, which can be helpful in all stages of surgical or other types of interventions, without affecting the duration of the procedure or the incidence of complications. This system has potential
advantages over conventional frame-based and frameless stereotactic procedures for the safety and effectiveness of surgical interventions. Its full clinical potential is not yet realized, and its overall effect on outcomes is not known. Nevertheless, this initial phase has already provided enough encouraging findings and promising results to justify our further engagement.

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