Clinical-patient studies

3-Tesla intraoperative MR imaging for neurosurgery

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Summary

Intraoperative magnetic resonance (MR) image-guided neurosurgery has been performed since 1994. Using a 1.5-Tesla (T) intraoperative MR imaging system, we have performed more than 750 interventional procedures. Having validated the safety and efficacy of this surgical technique that is relatively amenable to nearly all new in-hospital MR suites, we sought to adapt this approach at our sister hospital where a new short-bore 3-T MR suite was being installed. Using many of the lessons learned from our initial experience at 1.5-T, we designed a new interventional suite that would enable surgery to be performed entirely within a 3-T MR environment. All surgical instrumentation including electrocautery, fiberoptic headlamp, power drill, and ultrasonic aspirator was entirely MR-compatible. A few items with limited ferromagnetism were utilized within the magnetic field under strict precaution. From 2/04 to 7/05, those cases initially performed within the 3-T surgical suite included one drainage and reservoir placement for a cystic craniopharyngioma, five brain biopsies and two craniotomies; one for open brain biopsy and another for lesion resection. The craniopharyngioma was successfully aspirated and had the reservoir catheter placed within the cyst. All five brain biopsies yielded diagnostic tissue. The craniotomy for mass resection demonstrated radiation necrosis. Although the metallic artifact from the biopsy needle was more prominent than at 1.5-T, accurate image interpretation was possible. Surgical needles, disposable scalpels, disposable razor, and surgical stapler were minimally ferromagnetic and safely controlled by the surgeon. There were no adverse events associated with any procedure. MR-guided neurosurgery can be safely and effectively performed at 3-T. The surgical environment at 3-T is comparable to that present at 1.5-T.

Introduction

Intraoperative magnetic resonance (MR)-guided neurosurgery has been a clinical entity for more than a decade. Both neurosurgeons and radiologists have recognized the benefit of having the ability to image the brain during surgery in near-real time using MR [1–8]. Specific problems encountered at surgery where intraoperative MR imaging can provide the clinician with valuable information that will alter decision making include brain shift, defining the margins of low grade brain tumors by visual inspection, and the ability to readily identify potential complications that occur outside the surgical field. Despite technical challenges that have arisen during the development of intraoperative MR-guided neurosurgery, a variety of systems have been implemented and significant surgical experience has accumulated.

Initially, the focus of our interventional MR program was the treatment of vascular lesions such as acute stroke and the suite was designed to reflect this area of interest. The MR scanner was at the far end of the room and the digital subtraction angiographic equipment was outside the 5 Gauss line in the near end of the room. While other intraoperative MR sites housed specially designed scanners, our program adapted a conventional 1.5-Tesla (T) MR scanner for interventional use in order to demonstrate the feasibility of performing MR-guided procedures in any hospital where diagnostic MR imaging was available. Since the implementation of our interventional MR program we have proved the safety and efficacy of our approach in over 700 neurosurgical procedures.

The majority of our neurosurgical procedures have been performed outside the 5 Gauss line utilizing standard surgical instrumentation. In this approach, the patient is shuttled back and forth into the MR scanner for periodic imaging updates to monitor the progress of the surgery and to assure that the goals of the procedure were being met. More recently, we can now perform the entire neurosurgical procedure within the magnetic field at the far end of the room behind the scanner where the operative field extends beyond the flared opening of the magnet. Because having two surgical areas, within the same operative suite seemed redundant, we designed the 3-T operative suite to require entirely MR-compatible instrumentation with the surgical area located at the far end of the magnet. The new 3-T interventional suite is comparable in size to a 3-T diagnostic MR imaging suite with a slightly enlarged surgical area at the far end of the scanner. We have undertaken and completed four brain biopsies, two craniotomies, and one cyst aspiration with catheter placement uneventfully within this new 3-T surgical environment.
Methods and patients

3-T suite design

The total size of the 3-T intraoperative MR suite is 1700 square feet, which contains the control area (30 square feet), a patient prep and recovery area (120 square feet), a computer room (175 square feet), and the radiofrequency shielded room (583 square feet) that contains the magnet. The floor to ceiling dimensions in the room were 8’10” behind the magnet and 8’3” in front of and around the magnet. The size of the surgical theater behind the scanner was 167 square feet. Positive pressure ensured the preservation of a sterile surgical filed. A surgical equipment room with a radiofrequency door and a glass window housed the bipolar surgical cautery, air pressure driven footpad for the electrocautery, and the fiberoptic headlight. This closet was shielded only from the MR suite itself outside the radiofrequency shield. Adjacent to the back of the scanner, an anesthesia column was installed with a full array of anesthesia (oxygen, nitrous) and surgical connections (nitrogen for power drill, suction, filtered electric outlets).

3-T suite equipment

The 3-T MR scanner (Intera, Philips Medical Systems, Best, The Netherlands) is a fully functional diagnostic scanner with cardiac and neuro gradients that measures 157 cm from front to back and 78.5 cm from the rear flared bore opening to the isocenter. Recently, a table extender was added to the surgical table top to enhance access to the head at the rear of the magnet by increasing the posterior extension from 33 to 66 cm. Presently, Trendelenburg and reverse Trendelenburg positioning are not available however supine, angled supine and prone positions are possible during surgery.

An interactive scanning mode is available on the console in order to obtain rapid single slice scanning in any plane that allows for essentially near-real time imaging. This interactive mode enables rapid changing of the scan plane and the scan parameters, such as phase and frequency swap which minimizes the metallic brain biopsy needle artifact. An in-room, flat liquid crystal display (LCD) with trackball and scanner console capabilities is suspended from the ceiling on a rotating arm that is 100 cm from the rear opening of the magnet. Surgical illumination is provided by a suspended high-intensity surgical light (Sunnex Celestial Star CS2050, Sunnex, Natick, MA) with a wide range-of-motion and individual surgical headlights (Welel Allyn, Skaneateles Falls, NY). The MR-compatible anesthesia and monitoring equipment includes the Aestiva5/MRI ventilation and gas machine (Datex-Ohmeda, Helsinki, Finland), 3155A and 3150 monitors (Invivo (Intermagnetics), Orlando, FL) and infusion pump (Medrad, Indianola, PA) and pole.

3-T MR-guided brain biopsy

The patient is transported from the pre-induction area to the 3-T MR suite where general anesthesia is administered after intubation. The patient’s head is placed in the surgical position with two phased array radiofrequency coils positioned adjacent to the head in a SENSE pair. As previously demonstrated on the 1.5-T system, as long as the coils are not placed perpendicular to B₀ there is sufficient signal for high-quality imaging. One coil is usually placed underneath the patient’s head on a foam rubber donut and the other coil is placed opposite to the first. With the head in the operative position, MR-visible markers are placed on the scalp at the location where cranial perforation is anticipated. Baseline MR turbo FLAIR (fluid-attenuated inversion recovery), ultrafast T2-weighted half-Fourier acquisition single-shot turbo spin echo (HASTE), and T2*-weighted gradient echo scans are obtained before surgery in order to compare them to similar scans after surgery to exclude the presence of hemorrhage. After the scans are complete, the patient is advanced out the back end of the scanner and the scalp is shaved with a disposable razor with a plastic handle that is minimally ferromagnetic. The scalp is prepped with Duraprep (3M, Minneapolis, MN) and one coil is wrapped in gauze and then sandwiched between two sterile plastic adhesive drapes. This coil is then stapled to sterile surgical towels placed around the surgical site. A clear plastic sterile drape with an Ioban center and irrigation collection bag (3M, Minneapolis, MN) is applied to the surgical field and the adhesive back side is attached to the back of the scanner in such a manner as to allow patient transport to isocenter. A disposable scalpel bearing a plastic handle (Sandel safety scalpel, Sandel Medical, Chatsworth, CA) is used to incise the skin. Repeated testing has demonstrated that the ferromagnetic force on the scalpel does not exceed that of gravity unless the blade is placed within 38 cms of the rear opening of the magnet. Bipolar electrocautery (Codman, Raynam, MA) is used to control scalp and dural bleeding. A burr hole is made with an MR-compatible pneumatic drill (Maestro Medical, Dallas, TX) and the Navigus trajectory guide (Image-Guided Neurologics, Melbourne, FL) base is anchored in place with three titanium self-tapping screws (Figure 1). The patient is then advanced back into the scanner in order to perform prospective stereotaxis.

Prospective stereotaxis allows the surgeon to target the tumor in near-real time and has been previously described. Prospective stereotaxis is a novel way to determine the surgical path for the brain biopsy needle using a trajectory guide that starts at the site for biopsy and moves away from the target toward the distal end of the alignment stem. After the biopsy location (target point) has been chosen, it is necessary to identify two additional points in space in order to align the trajectory guide with the target. The second point is located at the tip of the alignment stem and is called the pivot point. The third point is located out in space and represents the desired location for the cross section of the alignment stem. The alignment stem can be oriented until all three points are collinear; thereby assuring that the passage of the biopsy needle through the trajectory guide will encounter the target.

After the alignment stem is filled with an appropriate fluid for visualization on MR imaging, it is then inserted