World’s first magnetic resonance imaging/x-ray/operating room suite: a significant milestone in the improvement of neurosurgical diagnosis and treatment

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Object. In February 2006, the magnetic resonance/x-ray/operating room (MRXO) suite opened at the authors’ institution. This is the first hybrid neurosurgical procedure suite to combine magnetic resonance (MR) imaging, computed tomography (CT), and angiography within a neurosurgical operating room (OR). In the present paper the authors describe the concept of the MRXO as well as their first 10 months of experience using this suite, and discuss its advantages and limitations.

Methods. In the MRXO suite, the combined OR and angiography (OR–angiography) station is located in the middle of the suite, and the MR imaging and CT scanning stations are each installed in an adjoining bay connected to the OR–angiography station by shielded sliding doors. The surgical, MR imaging, angiography, and CT tables are positioned in order of use. The patient lies on a fully MR imaging– and radiography-compatible mobile patient tabletop that is used to move the patient quickly and safely among the tables in the imaging and operating components of the MRXO suite.

Results. The authors performed all interventional procedures safely. The specially designed operating tabletop of the MRXO suite reduced the limitations on neurosurgeons during standard neurosurgical procedures. This hybrid suite helps to provide high-quality intraoperative imaging, greatly reducing the risk of unexpected events during the procedure.

Conclusions. The MRXO suite, which combines OR and imaging equipment, represents a significant milestone in the improvement of neurosurgical diagnosis and treatment and other interventional procedures. Another advantage of the MRXO suite is its cost-effectiveness, which is partly due to its streamlined imaging procedure.

(DOI: 10.3171/JNS-07/08/0266)

KEY WORDS • image-guided surgery • interventional procedure • intraoperative magnetic resonance imaging • intraoperative surgical planning • interventional procedure

Magnetic resonance imaging can help provide a noninvasive diagnosis, high soft-tissue contrast and physiochemical information, and can be used to obtain 3D reconstructions. This modality is no longer only used for routine diagnosis, but is also used during interventional procedures in many institutions. Computed tomography scanning, which is useful for diagnosis not only for soft tissues but also for bone and hemorrhagic lesions, provides a rapid imaging speed and the ability to obtain 3D reconstructions. Angiography is the modality of choice for many diagnostic procedures involving vascular imaging and for monitoring during endovascular interventions. Combining these diagnostic modalities allows for complementation of individual weaknesses, such as imaging speed, soft-tissue resolution, radiation exposure, and 2D projection imaging.

Intraoperative imaging is widely used in neurosurgery to allow surgical navigation systems to compensate for brain shift as well as to monitor hemodynamics during vascular surgery. In February 2006, our hospital officially opened the MRXO suite, which is a novel surgical suite that includes an interventional radiology system. This interventional surgical suite represents a major advance in the field of neurosurgery and will facilitate in the development of many new clinical techniques. In this paper, we describe this new imaging and surgical facility, report the results of interventional procedures performed using this suite, and discuss its advantages and limitations.

Clinical Material and Methods

Layout of the MRXO Suite

The MRXO suite consists of three separate adjoining
stations, each of which is located in one of three adjoining rooms. The combined OR and angiography (OR–angiography) bay is located in the middle room of the MRXO suite. The MR imaging and CT scanning rooms are located on opposite sides of the OR–angiography room (Fig. 1). The MR imaging and OR–angiography rooms are connected by a specially designed radiofrequency-, x-ray–, magnetic-shielded sliding door, which is 2800 mm wide, 2100 mm high, and 214 mm thick (Toda Corp.) (Fig. 2). The CT and OR–angiography rooms are connected by x-ray–shielded sliding doors. Each of the three rooms has a bay of imaging equipment; the three bays are arranged in a straight line, and the patient lies on a movable tabletop that is moved from table to table (Figs. 2 and 3).

The OR–angiography station is a fully OR-compatible system and includes surgical lights, laminar air flow with a microbiological filter ventilation system, electrical outlets, medical gas supplies, patient monitors, and a surgical navigation system (Fig. 3).

The CT room has an electrical outlet, medical gas supplies, and patient monitors for use in emergency bur hole surgery. The CT room has three doors: one that connects to the OR–angiography room, another to the technician’s room, and one to the emergency room. Thus, the patient can quickly be moved from the emergency room to the CT room to obtain the emergency CT scans.

Anesthesia and Monitoring

An MR imaging–compatible anesthesia machine (Aes­tiva/5 MRI, Datex) and monitoring system (S/5 MRI, Datex) are used in the MRXO suite. Because an infusion pump can easily be affected by high-frequency noise artifacts from an MR imaging unit, and because an infusion pump can easily induce radiofrequency artifacts in an MR imaging unit, the infusion pumps of the MRXO suite are...
covered by a special shielding box (Mizuho Ikakogyo Co.) (Fig. 5), so that the infusion pumps can safely be used in the MR imaging room without affecting the image quality.

Surgical Instruments

Generally, we do not use MR imaging–compatible instruments, with the exception of scalp clips and retractors for transnasal surgery. In the OR–angiography room, surgeons use routine ferromagnetic surgical instruments during surgery. Standard craniotomy and bur hole drilling are performed using conventional high-speed drills. A scrub nurse prepares all ferromagnetic surgical instruments, which are placed on the mobile nurse platform (Mizuho Ikakogyo Co.).

Fig. 2. Photographs.  Left: Specially designed radiofrequency-, x-ray–, magnetic-shielded sliding door separating the MR imaging room from the OR–angiography room.  Right: The patient, carried on a movable tabletop, can be transferred between each unit during the interventional procedure.

Fig. 3. Photographs.  A: Panoramic view of an MRXO suite (reprinted with permission from New Medicine in Japan 33:15, 2006). The OR–angiography room contains a fully OR-compatible system, including surgical lights, laminar airflow with microbiological filter ventilation system, electrical outlets, medical gas supplies, patient monitors, and a surgical navigation system.  B: View from the CT gantry, across the angiography table, to the MR imaging unit. All machines are positioned in an in-line alignment. If a patient requires both MR and CT imaging, the tabletop carrying the patient can easily be slid in-line between the MR imaging and CT rooms through the OR–angiography room.  C: The MR imaging–compatible tabletop is mounted on the mobile surgical operating table. This tabletop-mounted operating table allows the surgeon to position the patient in Trendelenburg or reverse Trendelenburg, rotate the patient to the right and left, let the feet hang down, tilt the head to an elevated or lowered position, and position the patient at the minimum or maximum height above the floor.
Co.) that protrudes over the operating table. The nurse platform also carries the high-speed drills, suction systems, electrocoagulator, and bipolar coagulator system. When images are obtained, all ferromagnetic surgical instruments, including the suction system, electrocoagulators, and retractors, are removed from the surgical field and operating tabletop, and are placed on the nurse platform (Fig. 6). A circulation nurse removes the nurse platform from the operating table, thus temporarily removing all non–MR imaging–compatible material.

Use of the MRXO Suite

The MRXO suite is suitable for a wide range of routine imaging and surgery, whether performed in conjunction or independently. The MRXO suite has proved its usefulness in interventional procedures involving the use of CT, angiography, and MR imaging.

For procedures in which MR imaging and angiography or CT and angiography are combined, the angiography table can be rotated in the direction of the MR imaging or CT bay, respectively. When MR imaging and angiography are combined, the connecting bridge must be placed between the MR imaging table and the angiography table. On the other hand, the CT table and angiography table are joined directly, and the tabletop can be moved in both directions. During imaging, the shielding door must be closed to eliminate imaging artifacts (Fig. 7).

For procedures that combine surgery and MR imaging (Fig. 7), the operating table can be placed toward the MR imaging bay, and surgery can be performed normally in that position. Intraoperative imaging can be performed at any time, provided that the usual precautions are taken to ensure a sterile environment. All ferromagnetic instruments are removed from the surgical field using the nurse platform, and the surgical wound is covered with a sterile drape. The connecting bridge is placed between the MR imaging–compatible tabletop-mounted operating table and the MR imaging table. The patient can be moved in and out of the MR imaging unit in about 10 to 20 seconds, but this does not include the time needed to remove the ferromagnetic surgical instruments and to adjust the surgical drapes; the checklist is completed by the on-duty safety nurse. The anesthesia machine and monitors are moved along with the patient. The results of imaging may determine the surgical approach by revealing the presence of a residual tumor that can be safely removed, often in areas that cannot be directly visualized using the surgical microscope. After the intraoperative imaging, the patient is returned to the primary surgical position, and resection continues.

For procedures that combine surgery and angiography (Fig. 7), the angiography table can be rotated 30˚ and connected to the operating table. The tabletop can then be moved back and forth between the two tables.

Results

Intraoperative MR Imaging

Patients with several kinds of intraparenchymal lesions (including glioma, metastatic brain tumor, and malignant lymphoma), pituitary adenomas extending to the suprasellar region, and cavernous lesions have been treated in the MRXO suite. All microsurgical procedures were performed using standard techniques.

We performed the following types of MR imaging sequences during surgery: routine T1-weighted with and without enhancement, routine T2-weighted, heavily T2-weighted, fluid attenuated inversion recovery, MR angiography, and diffusion-weighted imaging for fiber tracking (Fig. 8). High-quality images were obtained for all MR images.

The preparation times before MR imaging and surgery have gradually been reduced since the beginning of the MRXO project. Presently, the preparation time for MR im-

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**Fig. 4.** Photograph. With the connecting bridge positioned between the operating table and MR imaging unit, the patient can be moved into the MR imaging room. The anesthesiologist is holding the specially designed 9-m–long breathing tube system in his hand.

**Fig. 5.** Photograph of the specially designed shielding box for infusion pumps is shown on the left, and MR-compatible anesthesia machine is shown on the right. Both MR imaging–compatible anesthesia units can be brought inside the MR imaging room.
aging is 15 minutes, and the preparation time for surgery is less than 20 minutes. One to five MR images were obtained during each of the present surgical procedures. Most of the intraoperative images were obtained during the final stage of the surgical procedure and were followed by resection of a small residual lesion.

Safety Issues

The on-duty safety nurse is responsible for all safety issues. During preparation for the interventional procedure, this nurse reads aloud a checklist, and the surgical and interventional crews are required to follow the safety nurse’s instructions. The on-duty safety nurse is a member of the emergency department and is responsible for the safety education of new surgical and interventional crews. In the present series of patients, there were no accidents during patient transport or intraoperative imaging. Moreover, there were no infectious complications related to the neurosurgical procedures. During preparation for
imaging, the craniotomy area is temporarily covered with a sterile drape. After imaging, this sterile drape is removed from the patient’s head, and a new drape is applied to the craniotomy area. Using this draping technique, the sterile condition of the craniotomy area is maintained.

Nonneurosurgical Procedures in Which the MRXO Suite Is Used

In the field of interventional radiology, the MRXO suite is used for chemoinfusion or chemoembolization therapy for various malignant tumors, recanalization of occluded vessels, and embolization for portal hypertension and splenomegaly or gastric varices. During these procedures, angiography can be used to manipulate the catheter and continuously monitor the condition of the vasculature, while MR imaging and CT scanning can be used to monitor effects on the soft tissue. When a procedure requires multiple-modality imaging, the tabletop carrying the patient can be slid in-line through the open shielding doors between the three rooms of the suite, for reproducible imaging with minimal patient movement and time delay.

Routine Imaging Procedure

During the surgery in the OR–angiography room, the MR imaging and CT rooms of the MRXO suite are conveniently available for routine diagnostic imaging 24 hours a day. If a surgeon in the OR–angiography room wishes to take an intraoperative or other interventional image, the patient can be quickly moved from the OR–angiography room to the MR imaging or CT room. Immediately after the patient is returned to the OR–angiography room, the MR imaging and CT rooms are once again available for routine diagnostic imaging.

In the first 10 months since the opening of the MRXO suite, the CT scanner has been used for routine imaging in an average of 36 cases per day, the MR imaging unit has been used for 16 cases per day, and the angiography system has been used for one case per day. Thus, the MRXO suite is very useful for routine diagnostic procedures when it is not being used for interventional procedures.

Discussion

The MRXO suite, in which each modality independently is state of the art, provides an environment that allows exploration and assessment of integration of interventional facilities. An integrated interventional radiology system offers many advantages to the patient. To maximize these benefits, strategies can be developed that usefully combine information from multiple modalities. For example, MR imaging and CT (volumetric methods) can provide an integrated display of soft tissue, whereas x-ray angiography (2D projection methods) is useful for visualizing vascular...
structures. It is often helpful to match or superimpose images from different modalities during the diagnosis and/or treatment phase of an interventional procedure. Not only can MR imaging, CT scanning, and x-ray angiography be registered to provide combined images for interventional practitioners, but synthesized images derived from multiple MR images and directly reflecting physiological or metabolic parameters (for example, tissue oxygenation and blood flow) can also be registered and displayed in both x-ray angiography and MR imaging environments.

Intraoperative imaging plays an important role in neurosurgery, as it allows monitoring of the progress of the surgical intervention. Recently, various MR imaging systems specially designed for interventional procedures have appeared on the market. These include open systems with a standard low-field (0.3-tesla) system, a 0.5-tesla “double-donut” interventional system, and the unique Odin interventional system (0.12 teslas). However, because the field strength of an open system is unavoidably less than that available with a closed system, use of an open system always entails some sacrifice of image quality and acquisition speed. In many applications, this may be outweighed by the advantages of unrestricted access and a patient-friendly environment. However, the interventional radiology image quality (signal-to-noise ratio) and image acquisition speed are often equally as important as the interventional neurosurgical technique. For this reason, most neurosurgeons now prefer a hybrid system that provides maximum patient access within the constraints of full MR imaging functionality. Current 1.5-tesla MR imaging units provide all of the most advanced MR imaging features, including real-time interactive imaging, MR angiography, MR spectroscopy, MR thermometry, and functional modes such as functional MR and perfusion imaging. However, cost-effectiveness (including depreciation) is another issue that can influence the decision of whether to introduce a 1.5-tesla MR imaging unit into the surgical suite. When an MR imaging unit is installed in an OR, it is mostly used to assist with surgery. The depreciation of the MR imaging machine then depends on the turnover rate of surgery. The question then arises as to how often such an interventional MR imaging unit will be used. On weekends and holidays, the unit cannot be used in the operating suite, and on weekdays it is used for no more than four surgical cases per day. How can we justify the initial cost of introducing a 1.5-tesla MR imaging unit into the operating suite?

In 2001, the University of California, San Francisco, opened a unique twin-bay interventional suite combining an angiography system with a 1.5-tesla MR imaging unit. In this configuration, the angiography system and the MR imaging unit are each installed in one of two rooms. These two rooms are connected by a movable tabletop, which enables rapid transport of a patient back and forth between the two rooms while the patient remains on the same tabletop. A sliding door that is impenetrable to x-ray and radiofrequency radiation separates the two rooms. When the sliding door is closed, the two modalities can be used independently for two patients simultaneously. In the German cities of Erlangen and Heidelberg, a system is in use that has been designated the “twin operating theater,” in which independent MR imaging and surgical units are housed in two separate rooms. A radiofrequency-shielded sliding door separates these two rooms, and patients are moved between them on a patient couch.

When we read about these twin-bay and twin-OR systems, it occurred to us that intraoperative MR imaging would be an economical interventional system. The individual rooms of such a system can be used in combination for interventional procedures and can also be used independently for routine diagnostic procedures, or a combined routine imaging and interventional procedure; thus, the equipment is put to more economical use, and the cost-effectiveness of the equipment is improved.

Moreover, because our MRXO suite is located next to the emergency room, the suite is conveniently available for diagnostic imaging 24 hours per day, 365 days per year. In the first 10 months since the MRXO suite was opened, its CT scanner has been used for routine imaging in an average of 36 cases per day, and its MR imaging unit has been used for routine imaging in an average of 16 cases per day. The MRXO suite can be used not only for neurosurgical procedures but also for interventional radiology. When a patient in the emergency room requires interventional radiology, the MRXO suite can be used for CT, MR imaging, and angiography. Currently, angiography is a core procedure in the field of interventional radiology. For that reason, the angiography system is located in the middle of the MRXO suite.

The next issue is which other modalities should be combined with the surgical unit. Magnetic resonance imaging and CT are used for routine diagnostic procedures considerably more often than angiography, whereas neurosurgeons use intraoperative MR imaging and angiography more often than CT. For these reasons, the decision was made to combine the surgical unit with the angiography unit in the same room, and to install the MR imaging and CT units in two separate adjoining rooms.

The initial cost of modifying the imaging equipment increases their price by about 15%. The cost of a special-ordered MR imaging–compatible operating table and bridge depends on the size of the OR, but generally does not exceed $700,000. Construction and maintenance fees depend on the size of the hospital. One factor affecting the cost-effectiveness of the MRXO suite is the ease and frequency with which the imaging equipment, because it is shared, can be used for routine neurosurgical, radiological, and emergency medical diagnostic procedures and treatments.

Microscope-guided neurosurgery frequently requires changes in the patient’s head position (that is, elevation, descent, and right and left rotation) to follow the direction of the microscope light. The MR imaging–compatible operating tables typically have an inflexible flat tabletop. It has generally not been feasible to include joints in an MR imaging–compatible tabletop, because the materials usually available for hinges are not safe for use with MR imaging units or they give rise to artifacts on the resulting images. This lack of hinged MR imaging–compatible tabletops has made it difficult for neurosurgeons to change the head position of patients during microsurgery. It also limits the usefulness of intraoperative MR imaging for microsurgery. The MRXO suite includes newly designed operating tables that use a hinged MR imaging–compatible tabletop that can be bent during neurosurgery. This tabletop produces no artifacts on MR images, and it allows safe transfer of the patient between units of the MRXO suite. Thus, the MRXO suite includes a fully MR imaging–compatible
Hybrid interventional imaging and operation suite

operating tabletop that improves the effectiveness of intraoperative MR imaging.

Limitations of the MRXO Suite

The first limitation of the MRXO suite is that patients must be placed either prone or supine. Lateral positions are not possible, as the patient has to be moved through the magnet of the MR imaging unit, and there would not be sufficient clearance for the shoulders with the patient lying on his or her side. The second limitation is the time required to transfer the patient between the operating table and the MR imaging unit. This transfer takes a minimum of 30 minutes, because of the need to remove all ferromagnetic surgical instruments from the tabletop and the need to observe the safety protocol. The third limitation is that if a patient in the emergency room requires imaging while the appropriate imaging unit of the MRXO suite is being used for an interventional procedure, the former patient must be transferred to another imaging unit. In addition to the imaging units in the MRXO suite, our hospital has three angiography units, four CT scanners, and five MR imaging units available for obtaining images of patients in the emergency room.

Conclusions

The MRXO suite is a unique interventional suite that combines surgical and imaging units. It marks a significant milestone in improvement of procedural efficiency in neurosurgery and other medical fields. The MRXO suite is cost-effective for interventional procedures, and provides maximum patient access within the constraints of functionality of full imaging modalities. The specially designed hinged MR imaging–compatible tabletop-mounted operating table of the MRXO suite provides clear advantages for neurosurgeons over current nonhinged operating tabletops. Neurosurgeons who have used this MR imaging–compatible operating table have reported that it does not impose any new limitations on their actions, and that they are able to perform microsurgery in the usual manner.

Acknowledgments

We thank Mr. Atsushi Ito, Mr. Kazuhiro Sasajima (Philips Electronics Japan, Ltd. Medical Systems, Tokyo, Japan), Dr. Joop J. van Vaals, Mr. Denis Mioni, and Mrs. Elizabeth van Vorstenbosch (Philips Medical Systems, Best, The Netherlands), who developed the site plan of the MRXO suite and modified their imaging modalities to fit the MRXO suite. We also thank Mr. Noriaki Nemoto, Mr. Toshimi Shion, Dr. Daisaku Ikeda, Mr. Yasushi Kojima, and Mr. Yoshiaki Kono (Mizuho Ikakogyo Co., Ltd., Tokyo, Japan), who built the MR imaging–compatible operating table, connecting bridge, shield box, and other accessories. Finally, we thank Mr. Kazuaki Takemura and Mr. Masanao Ariga (Toda Corporation, Tokyo, Japan), who developed the initial plans for the MRXO suite and guided its development.

Disclaimer

None of the authors received financial support for this study. No author has an interest in any of the companies mentioned.

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Manuscript submitted June 24, 2006. Accepted January 26, 2007. Address reprint requests to: Mitsunori Matsumae, M.D., D.M.Sc., Department of Neurosurgery, Tokai University School of Medicine, 143 Shimokasuya, Isehara, Kanagawa 259-1193, Japan. email: mike @is.icc.u-tokai.ac.jp.