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Intraoperative MRI in neurosurgery: Technical overkill or the future of brain surgery?

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» Abstract

The development of image-guided neurosurgery represents a substantial improvement in the microsurgical treatment of tumors, vascular malformations and other intracranial lesions. Despite the wide applicability and many fascinating aspects of image-guided navigation systems, a major drawback of this technology is they use images, mainly MRI pictures, acquired preoperatively, on which the planning of the operative procedure as well as its intraoperative performance is based. As dynamic changes of the intracranial contents regularly occur during the surgical procedure, the surgeon is faced with a continuously changing intraoperative field. Only intraoperatively acquired images will provide the neurosurgeon with the information he needs to perform real intraoperative image-guided surgery. A number of tools have been developed in recent years, like intraoperative ultrasound and dedicated moveable intraoperative CT units. Because of its excellent imaging qualities, combined with the avoidance of ionizing radiation, MRI currently is and definitely will be in the future for the superior imaging method for intraoperative image guidance. In this short overview, the development as well as some of the current and possible future applications of MRI-guided neurosurgery is outlined.

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» Introduction

"... no technique in neurosurgery could be too refined, particularly in reference to the ability to localize lesions..."
Lars Leksell

Since the beginning of the nineties of the last century, the rapid development of navigational devices have provided the neurosurgeon with an unprecedented degree of surgical accuracy and precision for the planning as well as performance of a large variety of neurosurgical procedures.
In this context, the development of image-guided neurosurgery represents a substantial improvement in the microsurgical treatment of tumors, vascular malformations and other intracranial lesions. Despite the wide applicability and many fascinating aspects of image-guided navigation systems, a major drawback of this technology became apparent right from the beginning of its implementation in neurosurgical operations. All these neuronavigational systems use images, mainly MRI pictures, acquired preoperatively, on which the planning of the operative procedure as well as its intraoperative performance is based. As dynamic changes of the intracranial contents (brain shift) regularly occur during the surgical procedure due to tumor removal, the surgeon is faced with a continuously changing intraoperative field for which the preoperative data does not provide any information. Therefore, despite the use of high-tech navigational systems, from a certain point onwards, during the course of surgery, the neurosurgeon is still left with the information he gets with his eyes through the surgical microscope as well as his surgical experience. It is clear that only intraoperatively acquired images will provide the neurosurgeon with the online information he needs to perform real intraoperative image-

guided surgery.
A number of high-tech tools for use during neurosurgical procedures have been developed in recent years, like intraoperative ultrasound and dedicated moveable intraoperative CT units. However, for most experts in the field of intraoperative navigation and imaging it is absolutely clear that because of its excellent imaging qualities, combined with the avoidance of ionizing radiation, MRI currently is and definitely will be in the future, the superior imaging method for intraoperative image guidance. In this short overview, the development as well as some of the current and possible future applications of MRI-guided neurosurgery will be outlined.

» Development and clinical application of intraoperative MRI

Mid-field systems
The first intraoperative MRI, suitable and directly applicable for neurosurgical operations, was developed in 1991 by the combined efforts of the Departments of Neurosurgery and Radiology of the Brigham & Woman´s Hospital of the Harvard Medical School in Boston and the General Electric Medical Systems.
It led to the installation of the first prototype MRT system in the Brigham & Woman´s Hospital in 1994. This 0.5 Tesla system, the SIGNA SP, consists of two vertically placed superconducting magnets, which were oriented in a doughnut fashion leaving a gap of 56 cm, providing the space for surgery. The patient can be placed either between the two coils of the magnet or through the bore of the magnet leaving room for one or two surgeons. For RF transmission and receiving, a flexible head coil had to be developed, which could be placed into the sterile surgical field. Liquid crystal monitors mounted above the image region made it possible for the neurosurgeon to view the intraoperative images without leaving the magnet. A wide variety of directly MRI-compatible instruments, including an anesthetic delivery system, surgical instruments, a high-speed drill system as well as an MRI-compatible surgical microscope had to incorporated into the surgical environment. The first MRI-guided stereotactic biopsy was performed in June 1995 and the first craniotomy for brain tumor removal using the intraoperative MRI unit was undertaken in August 1996. In 1997 and in 1999, Black and Jolesz summarized their initial experiences with the development, implementation and neurosurgical application of MRI in two landmark papers published in NEUROSURGERY which set the stage for the more widespread use and possible acceptance of MRI technology during neurosurgical operations.[1],[2]
Additional sites with the 0.5 Tesla SIGNA SP system were almost simultaneously installed at the University hospitals of Zürich, Oslo, Tel-Aviv and Leipzig, where the author of this article had the opportunity to work with this system during 1996 to 1999 performing more than 300 intracranial procedures with the aid of this open MRI unit.[7]Experiences using the double-doughnut SIGNA SP system for neurosurgical interventions have up to now been continuously reported by several research groups from different hospitals.
Despite the apparent applicability and elegance of the double-doughnut open MRI concept with the possibility of performing procedures such as real time MRI-guided biopsies and "open-skull" procedures directly within the scanner, certain drawbacks also became readily obvious. Serious limitations were with increasing experience, with regard to patient positioning, space and access to the patient for the surgeon and nurse, severely compromised ergonomics, especially during long and complex operations, as well as the mandatory MRI compatibility of all instruments. Additionally, the question arose whether continuous intraoperative imaging is absolutely necessary during open craniotomy procedures, or whether it is desirable only during certain periods of the surgical procedure, e.g. to confirm radical tumor resection or to exclude complications at the end of the surgery.
Taking into consideration the above mentioned conceptual limitations of the SIGNA SP system, a different approach to MRI-guided surgery was proposed by the Siemens company which was clinically evaluated by research groups from the Departments of Neurosurgery of the University of Erlangen and Heidelberg.[8],[10] This concept consisted of a "twin operating theatre" incorporating a standard neurosurgical operating room equipped with a complete neuronavigation system. This concept allowed for neurosurgical operations in a standard environment, with standard MRI incompatible instruments and a standard surgical microscope being situated directly adjacent to a RF-shielded room equipped with a Magnetom-Open 0.2 MRI scanner. At any time during surgery the patient could be transported into the magnet, e.g. for resection control. The time of transportation varied between 20 and 40 minutes, thereby limiting the number of intraoperative image updates. Limitations of this interoperative imaging concept were seen by the inferior image quality due to the low 0.2. Tesla field of the Magnetom-Open system used, the increased costs of installation of an independent operating and scanning site, and most of all the necessity of time-consuming patient transportation during surgery. The advantages and disadvantages of the concepts of intra- and interoperative MRI are summarized in [Table - 1]& [Table - 2].

» High-field systems

Considering the limitations of both the available systems for intra- or interoperative MRI imaging, especially as regards field strength, a completely different concept was put forward in 1999 by Sutherland and co-workers. They published their preliminary results concerning the use of a mobile, actively shielded 1.5 Tesla Magnet. [9] While surgery is performed in a standard OR, the magnet is stored in an adjacent alcove separated from the operating theatre by closed doors. At any time during surgery, whenever required, the operative procedure is stopped, the operative field is draped and the ceiling mounted magnet is brought into the OR. An RF tent is placed over the patient and parts of the operating table, and the scanning procedure is performed. Apart from the considerable versatility of this concept, its major advantage lay in the use of a high-field magnet, allowing not only for the acquisition of high quality images but also for important additional functional capabilities of MRI like MR spectroscopy, functional MRI, MR angiography, chemical shift imaging, diffusion weighted imaging and more. Updates of data outside the magnet can be performed at any time by the use of a state-of-the-art neuronavigation system.

Almost parallel to the publication from Calgary a comparable concept was published by Hall and co-workers from the University of Minnesota, Minneapolis.[5] They used a standard 1.5 Tesla MRI system placed in a shielded operating room. Standard neurosurgical procedures were performed outside the 5 Gauss-line, obviating the need for special MRI-compatible instruments. In contrast to the Calgary concept, the patient has to be moved into the scanner if intraoperative imaging is desired. Although the distance from the operative area to the scanner could be considerably reduced compared to the Erlangen/Heidelberg concept, moving of the patient over a longitudinal distance of several meters is still cumbersome and time-consuming. However, an interesting feature of the Minneapolis site, was the creation of an additional surgical or interventional area directly behind the magnet in which completely MRI-compatible instruments have to be used. The groups from Calgary and Minneapolis were able to show wide applicability of a high-field system for neurosurgical procedures with excellent intraoperative image quality and also a wide range of additional functional applications.

A third concept incorporating a high-field system has been developed by a cooperative effort of the Siemens and BrainLab companies. It consists of a standard 1.5 Tesla MRI scanner, which is however completely integrated into a high-tech operative environment, incorporating a dedicated surgical suite with a state-of-the-art neuronavigation system and digitized image transfer and projection system. The patient is placed on a rotatable operating table. During surgery, the head or operative area of the patient is placed outside the 5 Gauss line so standard neurosurgical procedures can be performed with routine neurosurgical instruments and a standard surgical microscope. At any time during the operation, the surgical procedure can be interrupted, and the patient can be placed into the magnet by simple rotation of the operating table. Due to its high-field capabilities, excellent intraoperative images can be acquired, and all advanced functional imaging procedures can also be performed.

A separate operative area, directly behind the magnet can be used for interventional procedures or operations using the complete set of MRI-compatible instruments.

This completely integrated operative area, named BRAIN SUITE, which is scheduled for installation for the first time worldwide, at the University Clinic in Frankfurt/Main during the course of the year 2003, currently represents, with regard to high-field intraoperative imaging, the most advanced system in combination with neuronavigation, and with considerable future research possibilities.

Although highly desirable for neurosurgical intraoperative imaging and research, the major drawbacks of all high-field MRI units are that they are extremely expensive as regards installation and technical maintenance, as well as with regard to the necessary manpower and personal costs, making their installation procedure- and cost-effective only for high class academic or clinical centers with considerable resources and research prospects for intraoperative image guidance.

Very low-field system

In 2001 a novel, compact low-field system, developed jointly by the ODIN company, Israel and the Department of Neurosurgery of the Sheba Medical Center Tel Aviv, represented a completely different concept of intraoperative imaging during neurosurgery.[4] The system consists of an MRI scanner of only 0.12 Tesla field strength, integrated with an optical and MRI tracking system. Scanning and navigation, which are operated by the surgeon, are controlled by an in-room computer workstation. The scanner consists of two vertical, parallel, disk-shaped permanent magnets. These magnets are fixed to a U-shaped arm, which is mounted on a transportable gantry, which can be positioned under the operating table during surgery, where it is left, as long as no intraoperative images are required. During scanning the arm is raised, so that the area between the two magnets encompasses the head of the patient. The opening is wide enough to allow the surgeon surgical access to the patient's head, so that surgery can also be performed with the head of the patient lying between the two magnets. There are several conceptual advantages of this system: 1) only moderate modifications of a standard operating room are necessary, consisting especially of an RF-shielded cage; 2) with the magnet stored under the operating table, standard neurosurgical instruments can be used without problems; 3) the integrated tracking and navigation system allows for rapid and reliable intraoperative real-time navigation; 4) probably the most intriguing advantage of this system lies in the fact that it is completely under the control of the surgeon, obviating the need for radiological or assistant personnel.

However, there are also distinct limitations of this system, which are primarily due to its extremely low-field strength. The image quality, despite considerable improvement since the presentation of the first prototype systems, is still far from what is acceptable for routine intraoperative use during neurosurgical procedures. The application of functional imaging, spectroscopy or MRI angiography is not possible due to the low-field strength of this magnet. Currently, this system has to be seen more as a compact MRI guidance or navigation system, which in its concept as well as in its imaging capabilities differs significantly from the other systems described above.

However, if this system or comparable systems can be improved further, they may play a significant role during neurosurgical operations, and can probably be regarded as the navigation and intraoperative imaging systems of the future. And due to their relatively low costs as compared to mid- or high-field MRI units they may well be installed in large numbers of neurosurgical units [Table - 3].

» Conclusion

In this short review, only the major directions of current intraoperative applications of MRI technology, which can be divided into extremely low-field, mid-field, and high-field units, have been summarized. Modifications of these systems have been described by additional clinical research groups from different neurosurgical centers.[3],[6]

The intraoperative use of MRI imaging in neurosurgery has just started and future developments in this technology will surely add to the rapidly evolving field of MRI-guided neurosurgery. Currently, the question whether the implementation of an extremely costly high-tech tool like the MRI in the neurosurgical operating room represents a technical overkill restricted to only a very small number of high-class neurosurgical centers , or whether it is and will be a major breakthrough in modern neurosurgery cannot be answered. As an increasing number of intraoperative MRI units, whatever their field strength, will be installed in neurosurgical operating theatres worldwide, we have to await the increasing scientific evaluation of this technology, which will help to define the future role of intraoperative MRI.

However, if time and the increasing experience in MRI-guided neurosurgery demonstrate a significant benefit for the patient with respect to the postoperative quality of life and/or survival and if open MRI units can be integrated into neurosurgical clinics in a cost-effective manner with probable interdisciplinary, resource-shared use, it may well be that in the not-so-distant future, the integration of sophisticated MRI imaging may become the standard of care for neurosurgical patients.

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