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Preface

Intraoperative MRI Developments

Rudolf Fahlbusch, MD Christopher Nimsky, MD
Guest Editors

MRI has become a routine pre- and post-operative imaging modality in the treatment of brain tumors and epilepsy. In the last 20 years, significant progress in scanning technology has resulted in high-resolution three-dimensional anatomic imaging of the brain. In addition to anatomic imaging, information on function and metabolism in the individual patient is available. Since the mid-1990s, even the intraoperative application of MRI has been possible and has opened new avenues in immediate intraoperative quality control.

In this issue of *Neurosurgery Clinics of North America*, we focus on current MRI developments with an impact on intraoperative use in neurosurgery and on the intraoperative application of MRI technology. This issue compiles the contributions from a variety of experts in their respective specialties.

In the first part, a general overview of MRI techniques is followed by focusing on current developments with a distinct impact on intra-operative application, ranging from functional imaging with fMRI, to investigation of metabolism with magnetic resonance spectroscopy, to diffusion tensor imaging.

In the second part, a comprehensive and state-of-the art overview of the intraoperative application of MRI technology is provided. Experts using different low-, middle-, and high-field MRI systems available from 0.12 to 1.5 T focus on different aspects, such as integration of navigation, glioma resection, pituitary adenomas, biopsies, epilepsy, and functional imaging, followed by a perspective outlook.

With the development of open MRI systems in the mid-1990s, the concept of intraoperative imaging, up to then only realized with CT and ultrasound, experienced a renaissance. The first designs were based on low-field magnets, with magnetic field strengths up to 0.5 T. The use of MRI scanners in the operating environment for nearly 10 years has proved to be safe and reliable as well as applicable to neurosurgical procedures, even if these procedures have to be adapted to the MRI environment to a certain extent. Nevertheless, the optimal solution for intraoperative imaging setups, combining excellent image quality with smooth operating room work flow integration and ergonomic comfort for the neurosurgeon, still does not exist. All installed systems are prototypes with certain drawbacks. There are different concepts with respect to scanner and operating room design; intraoperative imaging necessitates operating directly in a scanner with the drawback of restricted space for the surgeon or some kind of intraoperative transport of the patient or the scanner itself. There are different operating table concepts, ranging from patient transport with an air-cushioned operating room table to an adjacent operating room, to movement of the patient along the longitudinal axis of the scanner to reach the

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fringe magnetic fields, to the use of some rotating mechanism with an operating room table adapted to the scanner. Also, the issues of MRI-compatible head fixation and coil design for intraoperative use have not yet been resolved without drawbacks. Regarding the overall operating room design, there are also different concepts, ranging from systems dedicated for intraoperative use only to hybrid systems combining intraoperative use with the application of the scanner for routine radiologic diagnostics.

To date, there is also no definite consensus as to which direction intraoperative MRI systems will develop. The current extremes range from low-field movable installations at 0.12 T up to concepts integrating ultrahigh-field strength imaging at 3 T in the operating room. Whether new scanner designs with larger and shorter bores or the application of different physical principles that allow flat MRI scanners (eg, below the operating table) will contribute to optimizing the intraoperative application of MRI technology further is not yet decided. Going to higher magnetic field strengths allows having a better signal-to-noise ratio, shorter scanning times, and a better resolution in certain modalities, such as functional imaging and spectroscopy. With regard to ultrahigh-field MRI, however, there may be increased problems with artifacts as well as geometric image distortions and restrictions caused by the specific absorption rates, because the deposited radiofrequency energy must be considered in the sequence design to obtain the same performance as in 1.5-T setups. Conversely, imaging techniques in the direction of ultralow-field MRI, which could be based on taking advantage of certain contrast media effects relating to the Overhauser effect, do not seem to be an alternative to anatomic patient imaging yet, even though some early success has been achieved in small animal imaging. The optimal solution would be a nearly invisible imaging system giving online real-time feedback to the neurosurgeon without disturbing the surgical work flow.

Meanwhile, it is agreed that intraoperative anatomic imaging is not sufficient alone. Intraoperative imaging has to be combined with intraoperative guidance, implemented, for example, in the form of microscope-based navigation. There has to be the possibility to use intraoperative images for guidance, allowing so-called "updating" of the navigation, which compensates for the effects of brain shift. Furthermore, and of paramount importance, is the integration of functional data, such as functional MRI (fMRI) identifying eloquent cortical brain areas and diffusion tensor imaging data identifying major white matter tracts as well as magnetic resonance spectroscopy for data on metabolism. All these functional modalities should also be available during surgery, reflecting the current status of the brain with respect to anatomy, function, and metabolism. Increasingly, detailed brain mapping, rendering the whole brain as "eloquent," has to address the problem of information overflow for the surgeon in the operating theater. In addition, adequate functional paradigms have to be developed further and standardized, especially with respect to their intraoperative application. Even nowadays, speech mapping by fMRI is not yet standardized enough for reliable pre- and intraoperative localization. In addition to guidance maintained by navigation systems, integration of robotic devices is under development.

Another important aspect of intraoperative MRI is its acceptance in overall society. This seems to be no problem with regard to the patients benefiting from this technology; however, acceptance is still ambivalent among physicians, public opinion, and politicians as well as health insurance providers. Intraoperative imaging per se seems to be more and more accepted as immediate quality control during surgery. In the case of high-quality intraoperative imaging, early follow-up imaging (up to 3 months) is not necessary any longer. Intraoperative MRI is in competition with ultrasound and CT as an alternative intraoperative imaging modality, however. Recent technical developments, especially in the field of CT, allowing high isotropic resolution, may have the consequence that these imaging technologies have to be considered as alternative intraoperative imaging modalities in neurosurgery, especially if economic restrictions are considered. Detailed economic analyses exceeding previous preliminary cost-benefit analyses must address these aspects. Preliminary results presented recently by Hall et al [1] have to be extended and evaluated on a broader platform for industry, insurance companies, politicians, and physicians. Furthermore, the significance of MRI as an intraoperative imaging modality has to be seen in competition with other imaging modalities, especially in operating room setups designed for the simultaneous use by other surgical disciplines.

In the future, perhaps as an alternative to the expensive and highly advanced setups allowing the identical armamentarium for pre- and intraoperative diagnostics, it will be possible to have a less cost-intensive system for intraoperative imaging. Such a system, based on whatever imaging modality, must generate detailed anatomic information about the intraoperative situation in which preoperative data on function and metabolism have to be integrated applying advanced mathematical techniques, including nonlinear registration techniques as well as mathematical simulations and models. None of these techniques are yet robust and time-efficient enough that they can be applied for intraoperative use.

Intraoperative imaging is well established, especially with respect to the completion of surgical resections in complicated procedures; however, it is an open question as to which direction intraoperative imaging will take. The problem of the practicability of intraoperative MRI is under investigation, whether it is in the hands of neuroradiologists and performed by them or by neurosurgeons. Intraoperative MRI varies from simple image generation to advanced image processing at a high scientific level. The experts working on the latter level should be obliged to present their findings on the application of the method objectively.

Reference

[1] Hall WA, Kowalik K, Liu H, Truwit CL, Kucharezyk J. Costs and benefits of intraoperative MR-guided brain tumor resection. Acta Neurochir Suppl 2003;85:137–42.

Rudolf Fahlbusch, MD
Department of Neurosurgery
University Erlangen-Nuremberg
Schwabachanlage 6
91054 Erlangen, Germany

E-mail address: fahlbusch@nch.imed.uni-erlangen.de

Christopher Nimsky, MD
Department of Neurosurgery
University Erlangen-Nuremberg
Schwabachanlage 6
91054 Erlangen, Germany

E-mail address: nimsky@nch.imed.uni-erlangen.de