

# A Review of Cranial Imaging Techniques: Potential and Limitations

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Traditionally, neuroradiologists provide the images for the neurosurgeon. However, the surgical demands on the images are often different from the diagnostic demands of the neuroradiologist. Nowadays, neurosurgeons expect a multimodality multidimensional visualization of the lesion or surgical target including the neighboring anatomical structures and the structures along the surgical trajectory/corridor. Such multimodality information may include morphological, functional, and metabolic data.

Physics, mathematics, and computer sciences have gained a growing impact on the development in this field. Based on mathematical formulas, such complex three-dimensional (3-D) multimodality data can be generated and displayed. Numerous commercial products for image acquisition and processing have resulted from this and are available to neurosurgeons. The further improvement of this field is strongly linked with the scientific efforts and interactions from and between various clinical and theoretical specialties.

## DIAGNOSTIC CRANIAL IMAGING

The surgically relevant intracranial information may be of a different nature or quality, such as morphological, functional, electrophysiological, or metabolic. These aspects can be studied by various technological modalities preoperatively and/or intraoperatively: magnetic resonance imaging (MRI) scan, computed tomographic (CT) scan, positron emission tomography (PET), ultrasound, magnetencephalography (MEG), and 5-aminolevulinic acid (ALA) fluorescence. *Table 17.1* shows the domains of these modalities.

From a neurosurgical perspective, it is important to consider that the factor morphology has various relevant aspects: spatial resolution (morphological details), pathology detection (e.g., tumor border), and detection of relevant anatomical structures (e.g., vasculature).

Another important aspect in the neurosurgical evaluation of cranial imaging techniques is the availability of data, its reliability, and the integration of this information into the pre-

operative and intraoperative surgical decision-making process and the integration into the operating room (OR) workflow.

For brain tissue imaging, MRI scanning has a higher resolution compared with CT scanning, whereas CT scanning is superior in the display of bony structures such as the complex cranial base. Cranial vasculature can be visualized in great detail by both techniques and both can be used preoperatively and intraoperatively.

In comparison to MRI scanning, ultrasound has a limited spatial resolution for brain tissue and cannot be used preoperatively but it represents the most user-friendly intraoperative imaging tool. The best subjective visual orientation is provided when the lesion is located in proximity to midline structures such as the falx cerebri and the ventricles.<sup>26</sup> Ultrasound can also be combined with a navigation system to display the localization of the probe in three dimensions and/or for updating the MRI scan-based navigation information for correction of brain shift.<sup>25</sup> The latter allows continuous tumor resection. Furthermore, ultrasound angiography allows online visualization of major intracranial vessels and was found to be helpful in identifying hidden vessels adjacent to and inside the tumor in approximately one-third of surgical cases.<sup>17</sup> However, the visualization capability is still limited to subjective evaluation and to purely morphological information.

MEG is today available in more than 100 institutions worldwide. For neurosurgical purposes, MEG is primarily used to localize neurophysiological/functional information and it provides a very high accuracy and resolution to identify language functions.<sup>6,8,10</sup> Its major drawback is that it cannot be used intraoperatively.

*Table 17.1* clearly shows that MRI scanning, among both preoperatively and intraoperatively available imaging technologies, offers the greatest variety of information and at the same time the highest quality in most of the surgically relevant parameters (resolution, tumor border, functional, metabolic, and vascular parameters).

A new level of visualization is offered by the so-called hybrid imaging, in which different imaging tools are combined in one environment, such as PET-CT and, as a latest development, MR-PET, which joins the great possibilities of MRI scanning with those of PET. Beyond the simultaneous

**TABLE 17.1.** Domains of cranial imaging technologies<sup>a</sup>

|            | Preop use | Intraop use | Resolution   | Tumor border | Functional | Metabolic | Vascular |
|------------|-----------|-------------|--------------|--------------|------------|-----------|----------|
| MRI        | Yes       | Yes         | +++          | +++          | +++        | +++       | ++       |
| PET        | Yes       | No          | ++           | ++           | +          | +++       | —        |
| CT         | Yes       | Yes         | + / +++ bone | +            | —          | +         | +++      |
| MEG        | Yes       | No          | +++          | +            | +++        | +         | —        |
| Ultrasound | No        | Yes         | +            | ++           | —          | —         | ++       |
| ALA        | No        | Yes         | +            | ++           | —          | —         | —        |

<sup>a</sup>Preop, preoperative; intraop, intraoperative; MRI, magnetic resonance imaging; PET, positron emission tomography; CT, computed tomography; MEG, magnetencephalography; ALA, aminolevulinic acid.

acquisition of morphological MRI scan and metabolic PET scan images, this technique will allow to combine various functional and metabolic images from both sources.

The use of MRI scanners with higher field strengths offers faster acquisition times and higher blood oxygen level dependent (BOLD) signal-to-noise ratios, and allows advanced functional MRI (fMRI) scanning. This results in a more detailed mapping of brain functions, especially of cognitive aspects—great impact in this field is presently being provided by neurologists and also by neuropsychologists.

However, it will require further research to evaluate the usefulness and applicability of such imaging data—a more detailed cortical mapping—for neurosurgical interventions and, finally, the benefit for the patient. Furthermore, the permanent development in this field with 7- and 9.4-T MRI scanners, for example, can potentially have a great impact on sophisticated procedures in neurosurgery.

### INTRAOPERATIVE CRANIAL IMAGING

Intraoperative CT scanning has its domains in visualizing cranial base structures, monitoring of stereotactic procedures, and spine surgery. Tumor resections, for instance, in meningiomas have been demonstrated, however visualization of gliomas in surgery is still superior in the MRI scan, because of its higher resolution of soft tissue. This is also true with the modern 64-slice CTs, which have the advantage of higher resolution and faster acquisition time compared with conventional CTs, however, they offer a high number of thin slices, requiring special filtration procedures to provide useful data for diagnostic and therapeutic purpose. Both CT and MRI scans offer excellent resolution to define vascular structures preoperatively and intraoperatively.<sup>1,24</sup>

Intraoperative fluorescence imaging with ALA is primarily used in malignant gliomas. By the use of white light, a necrosis can be clearly identified, but the exact delineation of tumor margins is not possible. Violet-blue illumination (using ALA), however, has the power to better show the tumor borders. A recent clinical multicenter Phase III trial showed a complete resection of contrast-enhancing tumor in 65% of cases when

ALA was used compared with a 36% complete resection rate using white light only.<sup>22</sup> This technique helps many neurosurgeons to improve the radicality of tumor resection. However, the future of cytoreduction as a principle of tumor surgery may be based more on complementary methods, such as metabolic imaging with magnetic resonance spectroscopy (MRS) angiography, MR-PET, or new developments in optical imaging such as optical coherence tomography<sup>3</sup> or multiphoton excitation of autofluorescence<sup>9</sup> for microscope-based scanning of the tumor resection plane.

At the present time, intraoperative MRI offers the greatest range in cranial imaging. Low-field and high-field scanners are available, which offer different imaging qualities and benefits for the patients and users, different acquisition times and imaging modalities, workflow challenges, and costs. High-field scanners are superior with regards to acquisition time, resolution, and image modalities; whereas workflow aspects and costs are more attractive in the low-field scanners. Low-field MRI scanners include 0.15-T ODIN (Medtronic), 0.2-T Siemens, 0.3-T Phillips, and 0.35-T Hitachi. The first intraoperative MRI scan was performed using a 0.5-T SIGNA SP, GE (Double Donut) for a biopsy of a brain tumor in Boston.<sup>2</sup> High-field 1.5-T MRI scan systems for intraoperative use were first offered by Siemens, followed by Phillips and General Electric. Diagnostic 3-T MRI scanners are offered by the same companies that provide 1.5-T scanners, and are used in the intraoperative setting. We estimate that, at the present time, there are approximately 60 intraoperative MRI scanners in use, the majority are ultralow-field scanners.

There are various concepts for the integration of MRI scanners into the OR environment. These concepts greatly depend on the field strength of the scanner and the available space and local infrastructure. Presently, there are two general principles being used: “magnet to the patient”<sup>23</sup> and “patient to the magnet”,<sup>7,15,21</sup> whereas continuous imaging within the magnetic field (patient and surgeon in the magnetic field) has not been pursued further.

**TABLE 17.2.** Additional lesion resection after intraoperative magnetic resonance imaging (MRI) scan

|               | 1.5-T MRI scan | 0.2-T MRI scan |
|---------------|----------------|----------------|
| Adenomas (16) | 36%            | 29%            |
| Gliomas (11)  | 41%            | 26%            |

Starting 10 years ago with a 0.2-T MRI scanner (Magnetom Open, Siemens)<sup>21</sup> and changing in February 2002 to a 1.5-T scanner (Sonata, Siemens), we can say that the image quality has improved in such a way that intraoperative MRI scan quality is equal to preoperative and postoperative imaging quality. The surgical benefit is best demonstrated by the improved lesion resection, as demonstrated in *Table 17.2*.<sup>11,16</sup>

The Erlangen high-field MRI scan experience, which started with a 0.2-T MRI scanner 10 years ago, included 686 procedures performed with the 1.5-T MR scanner (within the first 4 yr). The overall impact of MRI scan control on lesion resection or surgical strategy was given in 30% of all cases (*Table 17.3*).

An optimized use of imaging information is provided by the integration of functional navigation.<sup>12</sup> In a high-field environment the functional navigation equipment, as well as other OR equipment, has to be installed in a compatible fashion.<sup>7</sup> The concept includes a ceiling-mounted separated workstation connected with glass fibers in an optical multiplexing signal transmission (Vector Vision Sky, BrainLAB). Another important development is a special head fixation system with an integrated MRI scan coil and reference markers for an automated registration procedure for navigation (BrainLAB and Siemens).

The operating field is outside the 5-G line (approximately 1.5 m from the gantry of the scanner), allowing the use of conventional surgical instruments.

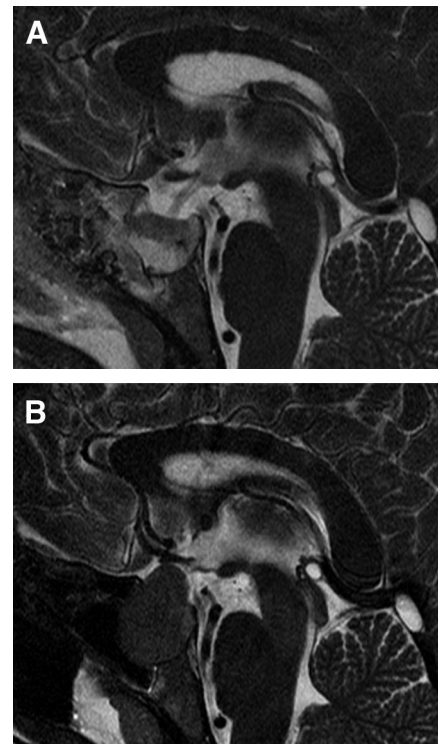
An intraoperative MRI scan procedure prolongs the operating time by approximately 20 minutes for every scan.

**TABLE 17.3.** Incidence of various lesions treated in Erlangen using the 1.5-T MRI scanner

| Lesion type                        | Number of patients |
|------------------------------------|--------------------|
| Glioma                             | 233                |
| Pituitary adenoma                  | 203                |
| Craniopharyngioma                  | 27                 |
| Cyst puncture in craniopharyngioma | 25                 |
| Nontumoral epilepsy                | 66                 |
| Miscellaneous brain tumors         | 132                |
| April 2002–January 2006            | 686                |

In general, one to three controls are needed for a tumor surgery. After the decision is taken to perform a control MRI scan and the appropriate covering of the operative field is performed, it takes approximately 2 minutes to place the patient's head into the gantry of the magnet. The transport of the patient is performed by means of a semiautomatic process on a rotating table. Thereafter, the first informative MRI scans can be obtained within 5 to 15 seconds (*Fig. 17.1*). In pituitary adenomas, for example, this quality is good enough to demonstrate tumor remnants and, thereby, to influence the decision-making process to continue tumor resection—if possible. Using longer acquisition times of approximately 12 minutes, total tumor resection can be documented, along with clear visualization of pituitary stalk and gland, optic nerves, and vessels. In a series of 84 resectable inactive macroadenomas, we could demonstrate that the use of intraoperative high-field MRI scanning increases the total resection rate from 57 to 84%.<sup>16</sup>

The use of high-field MRI scanning in glioma surgery provides the surgeon with the same variety of sequences (e.g., T1 weighted, T2 weighted, fluid-attenuated inversion recovery, echo-planar imaging) and image quality equal to preop-

**FIGURE 17.1.** A, sagittal T2-weighted MRI scan of an inactive pituitary macroadenoma with suprasellar extension. B, intraoperative sagittal T2-weighted MRI scan after tumor removal, with descending pituitary stalk and pituitary gland. Note the cerebrospinal fluid signal of the infundibulum. The optic nerve and the

erative imaging for a better evaluation of tumor resection and artifacts. Complete tumor resection, as well as invisible tumor remnants that are not distinguishable from healthy brain tissue can be visualized intraoperatively. The tumor margins can be segmented and transferred into the online (updated) navigation, superimposed in the microscope image onto the surface of the brain.<sup>12</sup> In addition, functional data such as sensory motor cortex, Broca's area, etc. can also be included, protecting important brain functions during surgery.

The benefit of intraoperative MRI scanning is mainly related to low-grade gliomas, partly to Grade III gliomas, and, to a limited extent, to glioblastoma multiforme.

Functional navigation was originally integrating—in addition to purely morphological images—a cortical mapping primarily based on preoperative data (e.g., fMRI, MEG). The use of intraoperative high-field MRI has opened up the possibility of intraoperative update of functional data with fMRI, thereby, also correcting the problems associated with brain shift.<sup>14</sup> Nowadays, functional navigation goes beyond the cortical level. Using diffusion tensor imaging (DTI) allows the display of fiber bundles such as the pyramidal tract.<sup>5,13</sup> However, complex computational analysis is necessary to perform such so-called tractography or fiber tracking. Commercial products are available that allow neurosurgeons to perform such DTI-based tractography within 12 to 15 minutes and to integrate this information, together with the cortical functional data, into the navigation plan. With this type of functional navigation, a 3-D model of the motor cortex can be visualized together with the pyramidal tract, and this information can then be superimposed into the microsurgical view on the brain surface and beneath. Intraoperatively, this can be repeated to correct the brain shift and to control for the relation of the tumor resection border to the pyramidal tract. In a series of 32 patients undergoing extended glioma resection, only one patient (3.1%) suffered from additional neurological deficit.<sup>12</sup>

MRS is another modality of high-field MRI scanners that offers, in addition to preoperative classification and differentiation of gliomas,<sup>19</sup> an option for improved radicality in glioma resection. Proton spectroscopy has shown that abnormal metabolic activity exceeds the tumor area in low-grade gliomas identified by T2-weighted MRI scans in 24% of cases.<sup>20</sup> We were able to integrate these metabolic images into navigation-guided tumor resection, thus, extending traditional cytoreduction as a modern principle in glioma resection. This will also include the intraoperative repetition of MRS for resection control beyond the morphological level.

## PERSPECTIVES OF INTRAOPERATIVE MRI SCANNING

Trends in the integration of intraoperative MRI scanning diverge between low-field and high-field scanners. 1.5-T MRI scanning is presently a robust and safe concept with a proven

benefit and the option for functional imaging. 3-T MRI scanning-related expectations are improved functional and metabolic imaging and, to some extent, faster image acquisition times. However, as soon as the 3-T related challenges will be solved, we and others will decide to switch to such therapeutically applicable 3-T MRI scanners: existing diagnostic 3-T MRI scanners have to be adapted to surgical concepts, including acceptable table transportation and compatible coils (integrated head fixation and automated registration for navigation), the scanner has to provide an open-bore gantry and self-shielding, allowing scanning procedures (draping) and surgery to be performed comfortably and in a short distance, and geometric imaging distortion has to be corrected.

Hybrid user systems combining access to the scanner to both neurosurgeons and neuroradiologists are already in use (e.g., Cliniques Universitaires Saint-Luc, Brussels, Belgium), expecting higher patient volumes. Other intraoperative 3-T MRI scanning installations are originating from MRI scanners used for diagnostic purposes.

Further plans aim to combine the OR with a 3-T MRI scanner and a PET-CT ("Amigo Suite Boston") or a MR-PET as well.

Our initiative at the International Neuroscience Institute (INI)-Hannover for intraoperative imaging started with a high-field open-bore 1.5-T MRI scanner (Siemens Espree) (Fig. 17.2). The construction of the HF cabin and other MRI-compatible equipment is designed to also be suitable for a 3-T MRI scanner. Thus, as soon as the above-mentioned challenges for 3-T MRI scanners are achieved, a new 3-T MRI scanner can replace our present 1.5-T MRI scanner.



**FIGURE 17.2.** INI-Brain-Suite with a 1.5-T MRI scanner. Note the head fixation with the coil in the gantry and the console for the rotating table in front. On the right is a ceiling-mounted infrared camera and touch screen of the navigation system. On the left is a multivision navigation microscope. The curved line on the floor (right front corner) indicates the 5-G line.

Low-field MRI scanners, in comparison to high-field scanners, are more user friendly and economically attractive. The image quality should be increased by improved resolution using smaller regions of interest and/or improved coils.

However, the question raised by Schulder et al. : “Do we need full-function, diagnostic quality systems . . . or are most neurosurgeons best served by units that provide useful imaging?”<sup>18</sup> has to be opposed to high-field MRI scanning serving as a resource for functional-metabolic research of brain pathologies and their optimized surgical treatment. This is an individual decision depending on the local resources and the personal and institutional expectations.

The topic “The operating room of the future” as presented by Buchholz some years ago at this CNS meeting includes the “operating room, as a key component of the medical system,” which “achieve a new level of efficiency to stretch the limited resources available to meet the requirements for the population”.<sup>4</sup>

Further perspectives for intraoperative MRI scanning are the following: less cost-intensive systems should be provided, and improvement of ergonomic integration into the OR environment and workflow—a vision would be a nearly invisible and nearly online flat or tabletop magnet, integration of therapeutic devices (e.g., smart intelligent instruments, thermoablation).

Overlooking the last 10 years—a relatively short period for a new emerging field—of escalating resources in intraoperative imaging, we conclude that despite promising results, especially in gliomas, more knowledge regarding the ultimate surgical benefit for long-term survival and quality of life has to be documented. Such a scientific effort will allow the increasing establishment of this kind of adaptive tumor resection as a standard procedure.

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