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Intraoperative imaging with open magnetic resonance imaging and neuronavigation

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Abstract The Erlangen-concept of image-guided-surgery is based on the installation of an open magnetic resonance (MR) scanner (Magnetom Open, 0.2 T, Siemens AG) in a twin operating room in combination with two neuronavigation systems (Stealth NeuroStation, Sofamor Danek, MKM Zeiss). Since March 1996 this method has been used for a total of 402 patients, among them 44 children. In 214 patients, mainly with gliomas or pituitary adenomas or who needed surgery for epilepsy, we performed intraoperative MR imaging to monitor the extent of resection, allowing a second look for possible tumor remnants and also compensating for brain shift by an intraoperative update of neuronavigation. Functional neuronavigation, i.e. the combination of anatomical neuronavigation with functional imaging [e.g. magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI)] was used in patients with lesions in brain areas such as the motor and speech areas. For MEG we used a MAGNES II biomagnetometer (Biomagnetic Technologies, San Diego, Calif.) and for fMRI a 1.5 T Siemens Symphony MR scanner. So far we have treated 89 patients with functional neuronavigation. Our preliminary experience indicates that intraoperative MR imaging, especially in combination with functional neuronavigation, allows more radical resections with lower morbidity.

Keywords Intraoperative imaging · Magnetic resonance imaging · Anatomical and functional neuronavigation

Introduction

Ultrasound [5], computed tomography [1] and magnetic resonance (MR) imaging [7, 8] are in the process of evaluation as a means of monitoring the extent of resections. While ultrasound clearly has limitations of resolution and computed tomography does not allow free slice orientation and lacks sufficient soft tissue contrast, intraoperative MR imaging seems to have more advantages. However the installation of an MR scanner in the surgical environment poses several difficulties that are discussed below. We report our preliminary experiences in the set-up, performance and clinical outcome of intraoperative MR imaging. The implementation of functional imaging and neuronavigation ("functional neuronavigation") covers both anatomical and functional data [2–4, 6]. Both methods are a new approach in the neurosurgeon's armamentarium for the treatment of brain disease that helps in the achievement of more radical treatment and less morbidity.

Materials and methods

Our concept of computer-aided surgery with intraoperative MR imaging is based on an installation of a MR imager in a "twin operating theatre" in combination with two neuronavigation systems. This installation was used for a total of over 402 patients between March 1996 and October 1999.

Our twin operating theatre includes a conventional operating theatre with complete neuronavigation equipment (MKM, Zeiss, Oberkochen, Germany/Stealth, Sofamor Danek, Broomfield, CO, USA) which allows surgery with magnetically incompatible instruments, conventional instrumentation, and a microscope set-up. Adjacent to this conventional operating theatre is a radiofrequency-shielded operating room designed for the use of the intraoperative MR imager (Magnetom Open 0.2 Tesla scanner, Siemens AG, Erlangen, Germany). Inside this operating room are two operating sites (on the MR-table, outside the scanner) used in transsphenoidal pituitary surgery and for interventions directly in the scanner. To integrate the MR-system into surgical procedures specific adaptations were necessary. An operating table and transportation with an air cushion technique were designed. The patient's head is fixed within a ceramic head-holder and imaging procedures are performed with a separable head coil which can be sterilized. The intraoperative images can be viewed on an in-room display. The patient can be moved during the operation between the two operating theatres on a specially designed, air-cushioned operating table (the distance from the conventional operating room into the scanner is 4 m), while the head is fixed in an MR-compatible ceramic head-holder.

fMRI was performed with a 1.5 Tesla MR scanner (Magnetom Symphony, Siemens AG, Erlangen, Germany) using echo planar imaging (EPI). For both functional and anatomical imaging, 16 contiguous axial MR slices parallel to the AC–PC (anterior–posterior commissure) plane, ranging from the parietal operculum to the vertex (cortical surface), were acquired. The AC–PC plane was defined in a 3D anatomical MPRAGE-sequence [MPRAGE: magnetization-prepared rapid-acquisition gradient echo; echo time (TE) 4.3 ms, relaxation time (TR) 11.08 ms, flip angle 15 °, slab 180 mm, 120 slices, field of view (FOV) 250 mm, matrix 256×256]. Functional images were measured using a T2*-weighted EPI sequence (TE 62 ms, TR 114 ms, flip angle 90°, slice thickness 3 mm, FOV 200 mm, matrix 64×64, interpolated 128×128). Anatomical images were collected in identical positions using a T1-weighted spin echo sequence (TE 15 ms, TR 450 ms, flip angle 90°, slice thickness 3 mm, FOV 200 mm, matrix 256×256).The fMRI experiments consisted of three activation and three baseline (rest) periods. Motor activation (MEA: motor evoked activity) consisted of iterative clenching of the hand contralateral to the lesion once per second. Sensory activity (SEA: sensory evoked activity) was evoked with a pneumatically driven tactile stimulator that applied tactile stimuli with an interstimulus interval of 800 ms to the index finger contralateral to the lesion, using a finger clip. Functional activation maps were calculated with a cross-correlation analysis between measured and expected activation time course for each voxel, using the AFNI (Analysis of Functional NeuroImages) software package.

For magnetoencephalography (MEG) a 2×37 channel biomagnetometer (MAGNES II, Biomagnetic Technologies Inc., San Diego, Calif., USA) was used inside a magnetically shielded room (Vacuumschmelze, Hanau, Germany), with a single dewar placed above the central region ipsilateral to the lesion. Each patient's head shape was scanned relative to the MEG sensor with an electromagnetic 3D-digitizer (Isotrak, Polhemus, Vt., USA). The MEG sources were localized applying a single-current dipole model with a locally fitted sphere as a head model. MEG dipoles were localized for the first pronounced peak in the motor evoked field (MEF) waveform and for the M30 somatosensory evoked field (SEF) wave (latency 25–45 ms after stimulus onset). Only dipole sources showing correlation values greater than 0.95 between the theoretical and measured magnetic field distributions were accepted. The anatomical source location was performed with a contour fit algorithm, fitting the digitally scanned head shape including the MEG dipole to the patient's individual MRI data set. The SEF-, MEF-MEG and SEA- and MEA-fMRI data were matched on this 3D dataset using a contour fit, described elsewhere [4]. MEF-MEG is represented as a white pyramid (intensity 1000), SEF-MEG as a white cube (4×4×4 pixels). Accordingly a black pyramid (intensity 0) and cube represented MEA- and SEA-fMRI. This 3D dataset was then transferred via fast-Ethernet to the neuronavigation microscope MKM (Multiple Coordinate Manipulator, Zeiss, Oberkochen, Germany).

Results

Intraoperative MR imaging for monitoring resection was performed in 57 patients with a glioma adjacent to or in eloquent regions (WHO grade I 13, II 15, III 11, and IV 18). In three of the grade I tumors, the tumor remnants could be removed when a second look was taken, giving 100% removal. Nine out of 15 grade II tumors showed tumor remnants; in four of them removal was completed after the navigation update, so the rate of completion increased from 40% to 66%. Five patients with grade III tumors had tumor remnants and a further resection was performed in two. In eight patients (grades I–III) the tumor was not removed completely due to infiltration of eloquent brain areas. In 14 of the 18 glioblastoma cases no further resection was performed because of the extent and biology of the tumor.

In the course of the operation an increasing brain shift of up to 2 cm reduces clinical accuracy of the neuronavigation systems, which is dependent on the size of the tumor and the resection cavity, CSF drainage, and head placement. As ongoing neuronavigation was needed during the operation, despite decreasing clinical accuracy and for localization of the remaining tumor, intraoperative MR imaging for an update of neuronavigation was administered in 14 cases to compensate for brain shift, leading to high clinical accuracy and allowing the rest of the tumor to be resected at a second look during the same operation.

In surgery for temporal lobe epilepsy (n=52) intraoperative MRI was able to document the extent of the neocortical and mesial resection, which was individually tailored, as well as it could prove the complete excision of the lesion in the non-cryptogenic cases.

In surgery for suprasellar tumors (pituitary adenomas and craniopharyngiomas, n=45) the extent of resection of the intracranial tumor part could already be documented intraoperatively in more than 70% of patients without artifacts. In the majority of these cases this ultra-early result matched the late MR result, which normally is obtainable without artifacts no earlier than 2–3 months postoperatively.

In all 89 patients with lesions adjacent to the motor cortex, MEG and fMRI results were confirmed by intraoperative electrocorticography. MEG and fMRI correctly localized the motor and sensory cortex, but differed by up to 15 mm. In 68% of patients a macroscopic total tumor resection could be accomplished; in the remaining cases only biopsy or subtotal resection was performed, due to infiltration of the motor cortex. Thirty per cent of the patients improved from their state of preoperative

paresis, 64% remained unchanged, and only 6% had permanent deterioration of neurological function. Three patients with MEG-localization of speech-related areas were treated successfully without impairment of speech function.

Computer-aided surgery in children (n=44) was especially helpful in those with craniopharyngiomas, tumors in the pineal region, or low-grade gliomas.

Discussion

Our preliminary experience suggests that intraoperative MR imaging is a convenient tool for evaluating the extent of a resection intraoperatively, offering the possibility of a second look and compensation for brain shift. Despite the open question of whether long-term outcome for patients is improved by a more radical resection, intraoperative imaging gives a chance for more radical resections with fewer complications.

We conclude that the combination of functional imaging and neuronavigation is a helpful technique for surgery in or near functionally important brain areas, allowing more radical resection with less morbidity when supported by intraoperative MRI monitoring of the extent of resection. Functional neuronavigation with integration of fMRI and MEG allows fast identification of eloquent brain areas. Widespread availability of fMRI will result in a broad availability of functional neuronavigation, contributing to successful surgery of lesions in these areas.

The next steps in the future will be the development of better MR sequences that are less sensitive to artifacts and allow better differentiation between tumor and brain edema at the resection border. Furthermore there are efforts to avoid moving the patient during operations by operating on all of them on the movable table of the MR scanner itself, with a new microscope that can be used near the magnetic field still providing all navigational features, including functional neuronavigation. In addition to these developments the adaptation of a high-field MR system (1.5 Tesla) in the operating room setup, allowing shorter scanning times, higher image quality, and intraoperative vascular and functional imaging and MR-spectroscopy will open new possibilities for intraoperative imaging and functional neuronavigation.

References

1. Butler WE, Piaggio CM, Constantinou C, et al (1998) A mobile computed tomographic scanner with intraoperative and intensive care unit applications. Neurosurgery 42:1304–1310
2. Fahlbusch R, Ganslandt O, Nimsky C, et al (1998) Application of functional neuronavigation and open MRI in tumors of the central area and sella area (abstract). Zentralbl Neurochir [Suppl] 17
3. Ganslandt O, Fahlbusch R, Nimsky C, Kober H, Möller M, Steinmeier R, Romstock J, Vieth J (1999) Functional neuronavigation with magnetoencephalography: outcome in 50 patients with lesions around the motor cortex. J Neurosurg 91:73–79
4. Ganslandt O, Steinmeier R, Kober H, et al (1997) Magnetic source imaging combined with image-guided frameless stereotaxy: a new method in surgery around the motor strip. Neurosurgery 41:621–627
5. Jödicke A, Deinsberger W, Erbe H, et al (1998) Intraoperative three-dimensional ultrasonography: an approach to register brain shift using multidimensional image processing. Minim Invasive Neurosurg 41:13–19
6. Nimsky C, Ganslandt O, Kober H, Möller M, Ulmer S, Tomandl B, Fahlbusch R (1999) Integration of functional magnetic resonance imaging supported by magnetoencephalography in functional neuronavigation. Neurosurgery 44:1249–1256
7. Steinmeier R, Fahlbusch R, Ganslandt O, et al (1998) Intraoperative magnetic resonance imaging with the magnetom open scanner: concepts, neurosurgical indications, and procedures – a preliminary report. Neurosurgery 43:739–748
8. Wirtz CR, Bonsanto MM, Knauth M, et al (1997) Intraoperative magnetic resonance imaging to update interactive navigation in neurosurgery: method and preliminary experience. Comput Aided Surg 2:172–179