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Open MRI-Guided Neurosurgery

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Summary

Objectives. A number of different image-guided surgical techniques have been developed during the past decade. None of these methods can provide the surgeon with information about the dynamic changes that occur intra-operatively.

Material and Method. The first vertical open 0.5 T MRI-scanner for intra-operative MRI-guided neurosurgery in Germany was installed at the University of Leipzig during the summer 1996. Since autumn 1996 a number of surgical procedures including biopsies (n = 31), craniotomies (n = 32), transsphenoidal procedures (n = 8) and interstitial lasertherapies (n = 3) have been performed using intra-operative MR image guidance.

Results. The development of MR-compatible and MR-safe nonmagnetic instruments and components had to be solved. Specific surgical instruments were developed to perform biopsies, craniotomies, microsurgical tumour resections and transsphenoidal procedures in the 0.5-T open MRI. Several components required adaptation including the head holder, the stereotactic navigation device, the high speed drill, the suction unit, the ultrasonic aspirator, the bipolar coagulation, the laser probe and the surgical microscope. All these newly developed technical features enable the neurosurgeon to perform a large number of surgical procedures under direct control and guidance of intra-operative MR imaging. In contrast to frame-based for framless navigation systems, intra-operative MRI provides accurate and immediate information during the progress of surgery. These intra-operative images allow definitive localization and targeting of the lesions and accommodate anatomical changes that may occur during surgery.

Conclusion. Intra-operative MRI is helpful for navigation as well as determining of tumour margins to achieve a complete and safe resection of intracranial lesions. Complications related to the surgical procedure are reduced and the risk of neurological deterioration due to tumour removal and postoperative complications is minimized. It can be concluded that the intra-operative application of interventional MRI technology may represent a major step forward in the field of neurosurgery.

Keywords: Intra-operative magnetic resonance imaging; neuronavigation; tumour biopsy; brain tumours.

Introduction

During the past decade, navigational devices have provided an unprecedented degree of surgical guidance during neurosurgical procedures. The development of image-guided neurosurgery represents a substantial improvement in the microsurgical treatment of tumours, vascular malformations, and other intracerebral lesions. It allows a greater accuracy in the localization of the lesion, a more accurate determination of its margins, and a safer surgical removal, avoiding injury to the surrounding brain tissue. Currently available systems of image-guided surgery include both frame-based and frameless technologies. All these systems use images acquired pre-operatively to create a three-dimensional space on which the navigation during the whole neurosurgical procedure is based [1, 2, 5, 9–11, 17, 22, 28–30]. However, none of the current devices can provide the neurosurgeon with information about the dynamic changes (brain shift) which occur during the progress of the surgical procedure, due to tumour removal, brain oedema, and loss of cerebrospinal fluid. Additionally, these systems are not able to detect intra-operative adverse events and complications e.g. intracranial haemorrhage. The group of Black *et al.* were instrumental in the development and first implementation of the 0.5 tesla vertical open MRI for intra-operative guidance during different neurosurgical procedures e.g. surgery of brain tumours, drainage of intracranial cysts, spine surgery and interstitial hyperthermia [3]. Using the guidance of the

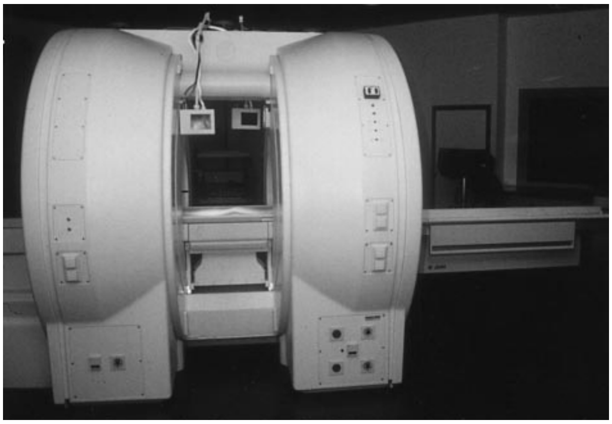

Fig. 1. Vertical opened 0.5 T MR tomograph "SIGNA SP" (General Electric Medical Systems, USA) with two in bore displays

0.5 T MRI Martin *et al.* described their experience with the removal of low-grade gliomas. A complete resection of the tumour mass with the aid of intra-operative guidance was achieved in 72% of their patients and a subtotal removal was achieved in 28% of their cases. Intra-operative imaging in these patients revealed residual tumour involving deep brain structures, speech center or motor cortex [18]. In this context we present our first experience with MRI-guided neurosurgical procedures including brain biopsies, microsurgery of brain tumors, transphenoidal surgery of pituitary tumours and clival lesions and interstitial laser therapy at the Department of Neurosurgery of the University of Leipzig, representing the first experiences in the use of a vertical open interventional MRI unit from a neurosurgical center in Europe.

Patients and Methods

Since autumn 1996 a number of surgical procedures including biopsies (n = 31), craniotomies (n = 32), transsphenoidal surgery (n = 8) and interstitially minimal invasive laser procedures (n = 3) have been performed using a 0.5 T superconducting MR system "SIGNA SP" (General Electric Medical Systems, USA) (Fig. 1). It has a vertical gap within its magnet, providing the space for surgery. Images are viewed on monitors located within the gap, which allow accurate intra-operative guidance and a correlation between the instrument position and the anatomical brain structures [20, 23, 26, 27].

For RF transmission and receiving a flexible head coil is used (Fig. 2a). The dimensions of the two coil loops connected at one side are 23×19 cm. In consideration of the access to the lesion through a small burr hole, craniotomy, or transphenoidal approach it was possible to attach the coil with a great variability to the patient's head (Fig. 2b). The flexibility of the coil is necessary for such a procedure. At the same time the flexibility causes the problem of instability of coil fixation in relation to the patients head. However, with increasing experience, a method of fixation was developed using drapes, pads and plasters, so that the head coil could be fixed in a relatively rigid position to the patient's head. Sterile coil drapes specially manufactured for this purpose are also available.

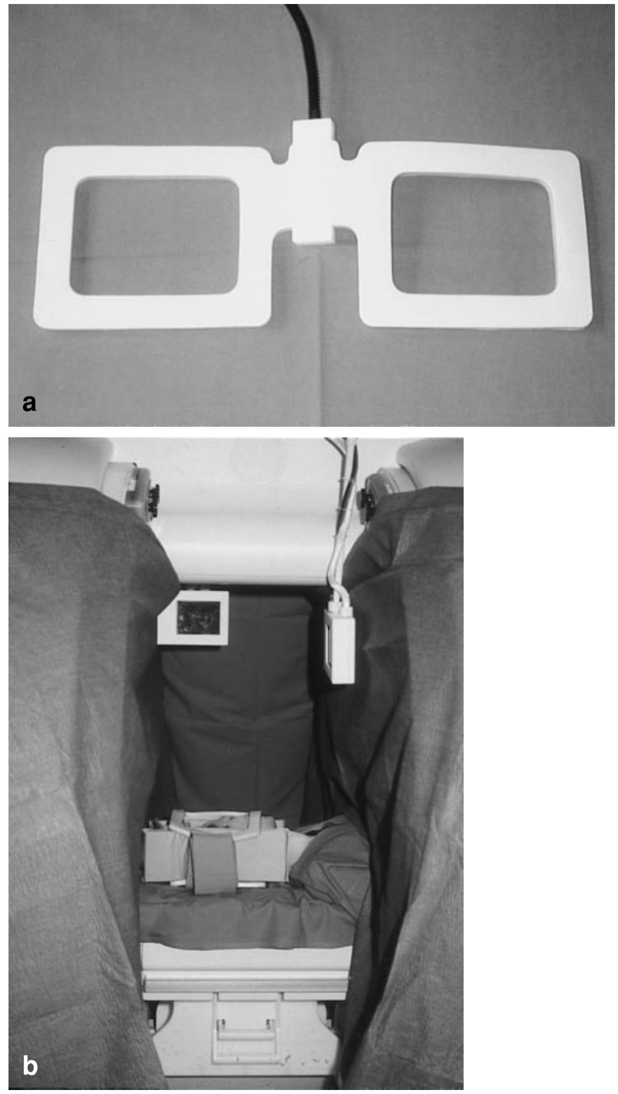

Fig. 2. Flexible transmit/receive coil. (a) Two loops opened; (b) fixed to the patients head before sterile draping the operation field

Liquid crystal (LCD) monitors mounted above the image region make it possible for the neurosurgeon to view the intra-operative images without leaving the MRI device (see Fig. 1). To permit interactive selection of the image plane a special LED tracking system "Flashpoint Position Encoder" (Image Guided Technologies, USA) is integrated. Thus it is possible to determine a scan plane and to control the position of an instrument, e.g. a biopsy needle, rigidly connected to the tracking system (Fig. 3a) or a blunt pointer (Fig. 3b). Using a common single slice gradient echo sequence with an acquisition time of 3 seconds per image the delay between a change of the tracking system position and the display of the corresponding image because of reconstruction time is about 7 seconds. In this the interactive mode could be used as a nearly real-time control for biopsies and during intra-operative guidance for all other micro-neurosurgical procedures.

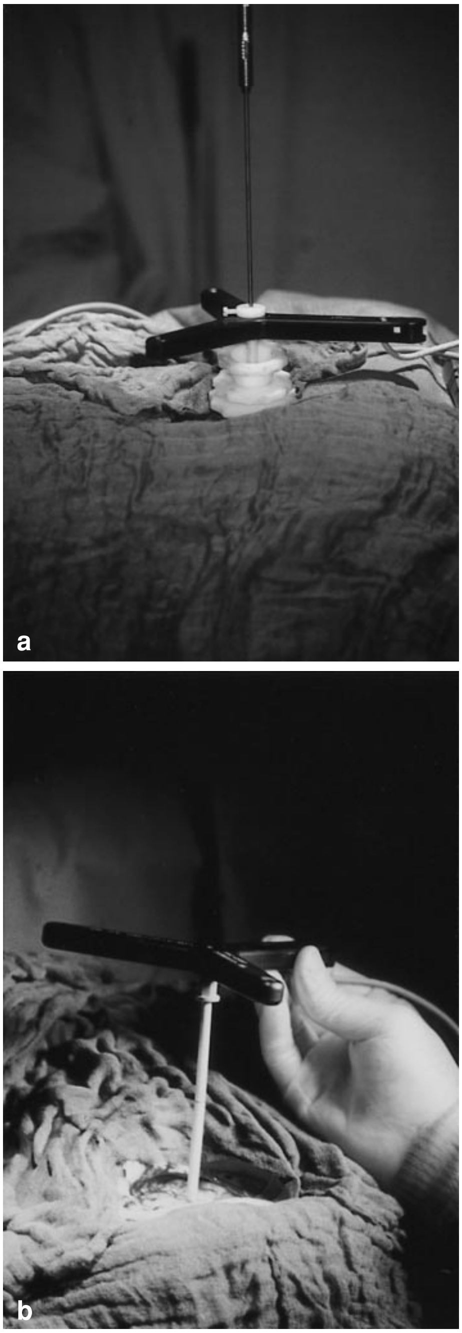

Fig. 3. (a) The use of LED-based optical tracking in combination with the burrhole snapper (Fa. Magnetic Vision, Switzerland) for the intra-operative guidance of the biopsy cannula (Sedan side-cutting needle, Fa. Elekta, Sweden); (b) LED-flashpoint and the blunt pointer in situ. The MRI compatible blunt pointer can be filled with water or gadolineum, depending on MRI sequence

In preliminary phantom experiments performed at our institution, small deviations from the optimum direction were noted when using the surgical instrument in combination with the LED interactive tracking system free hand. For this reason a special holding device was constructed. This frame allows one to attach the handpiece for controlling the scan plane during the operation. The holding device permits both a motion of the "Flashpoint" system in all three dimensions for the interactive guidance of the biopsy and a safe fixation of the tracker after adjusting an optimum biopsy direction.

The patient is positioned in the MRI in a way that the suspected lesion is situated near the isocenter between the magnets in combination with good access for the surgeon to the target area. For localization of the lesion fast T2w spin echo sequences and T1w spin echo sequences before and after injection of Gd-DTPA are used. Therafter the continuous interactive imaging mode with a gradient echo sequence is applied for which a T1w fast multiplanar spoiled gradient echo (TR = 24–30 ms, TE = 8–9 ms, flip angle 45°, rbw 16.6 kHz) with a single slice of 10 mm thickness is used. It was possible to obtain a new image every 3–4 seconds. Alternatively a more T2*w gradient echo sequence (TR = 35 ms, TE = 12.7 ms, flip angle 90°, slice thickness 10 mm, 7 seconds/image) for better visualisation of the ventricular system and the intracerebral vessels can be used. As a result of these pre-operative scans the position for the burr hole or craniotomy is planed directly centered over the respective lesion.

In the first 10 biopsies the burr hole trepanation was carried out in the normal operating theatre because some MR-compatible instruments were not yet available. After completion of the equipment, e.g. by the pneumatic drill system "Midas Rex" (Midas Rex Pneumatic Tools, USA), an electrocautery unit "ICC-350 MRI" (Fa. Erbe, Germany), an ultrasonic aspirator (Fa. Elekta, Sweden) and several neurosurgical instruments (Aesculap, Germany; Codman, USA) it is now possible to carry out the whole procedure within the MR unit. The anaesthesia is started outside the MR room. A MR compatible patient monitoring system and also a compatible respirator were necessary conditions for general anaesthesia in the scanning room. At our site we use the "Multigas Monitor" (MR-Equipment Corporation, USA) and the "Servo Ventilator 900 C" (Siemens, Germany) to continue anaesthesia inside the MR unit.

Results

MRI-Guided Biopsies

The first MR-guided biopsy of a brain tumour was performed in August 1996. Up to now 31 MRI-guided biopsies have been performed. No mortality or procedure related morbidity was associated with the MRI-guided biopsy in any of these 31 patients. 29 of these patients underwent frameless MR-guided biopsy. Two biopsies were framebased stereotactic biopsies with additional guidance of the interventional MRI. All lesions larger than 8 mm in diameter were detected in both the conventional 1.5 T MRI ("Vision", Siemens, Germany) and the 0.5 T MRI ("SIGNA SP", General Electric Medical Systems, USA) in different scanning modes (T2w, T1w before and after injection of contrast agent). The gradient echo single slice sequences used for intra-operative imaging did not allow an exact differentiation between tumour and surrounding brain tissue in all cases. It was easy to find the target for biopsy in lesions with an optimal contrast enhancement (Fig. 4). In 6 cases the biopsies did not result in a histological evaluation decisive for further treatment.

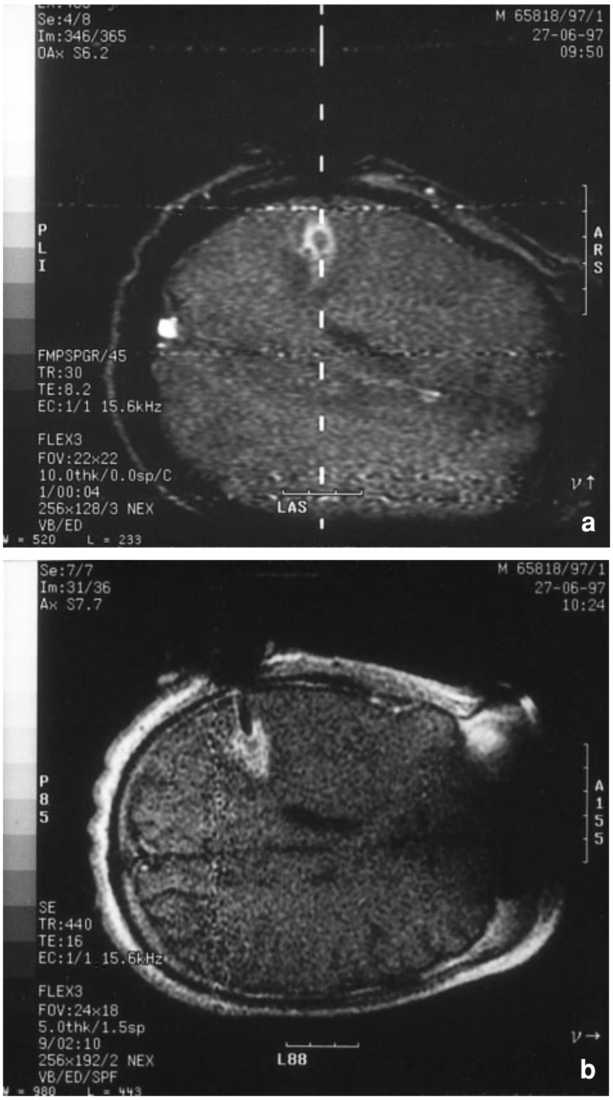

Fig. 4. (a) Use of the interactive scan guiding system creating a virtual needle (fast multiplanar spoiled gradient echo, 24/8.9/45, 10 mm slice thickness) for planning the biopsy direction; (b) After marking direction and calculation the distance of the target, tumour biopsy was carried out using a Sedan side-cutting biopsy needle (Fa. Elekta, Sweden)

One of those specimens revealed a tumour without possible further classification. 4 of these 6 biopsies were taken by aspiration cannulas. After changing the type of biopsy cannulas (Sedan sidecutting needle, Fa. Elekta, Sweden) a significant improvement in the histological evaluation was achieved. The histological results are presented in Table 1.

MRI-Guided Microsurgery of Intracranial Tumors

The first craniotomy for resection of an intracranial tumour was performed in August 1997. Subsequently, 32 craniotomies have been performed using the image guidance of the intra-operative MRI. Craniotomy and tumour removal were completely performed in the interventional MRI using non-magnetic surgical instruments for these procedures. The results of the histological evaluation are demonstrated in Table 2. The initial MR imaging allows the precise localisation of the intracranial lesion in relation to the patient's head and the surrounding normal brain, using the LED tracking system (Fig. 5). It is also useful for the planning of the craniotomy and trajectory of access to the lesion. During removal of the lesion, serial images are performed to guide the tumour resection as well as to control the radicality of tumour removal (Fig. 6). The use of gadolineum-DTPA may be helpful to determine the extend of resection. After tumour removal a slight enhancement occurs at the border of the surrounding brain which can be clearly differentiated from evidence of a solid tumour remnant (Fig. 7). The histological results are presented in Table 2. Intra-operative MR imaging is also a helpful tool for detection of intra-operative complications, e.g. haemorrhage. In this regard, in one patient an epidural haematoma was detected by intra-operative MRI at the end of the surgical procedure. The haematoma was immediately removed and the patient transferred to the intensive care

Table 1. *Histological Results of 31 Brain Tumour Biopsies in the Interventional MRI*

Histological examination	n
Astrocytoma (WHO II)	11
Astrocytoma (WHO III)	6
Glioblastoma (WHO IV)	2
Metastasis	3
Lymphoma	1
Abscess	1
Meningloma	1
No histology	6

Table 2. *Histological Results of 32 Patient with Intracranial Tumours Operated on in the Interventional MRI*

Histological examination	n
Astrocytoma (WHO II)	9
Astrocytoma (WHO III)	3
Oligodendroglioma (WHO II)	3
Dysembryoblastoma (WHO I)	1
Subependymoma (WHO I)	1
Glioblastoma (WHO IV)	9
Metastasis	3
Meningloma	3

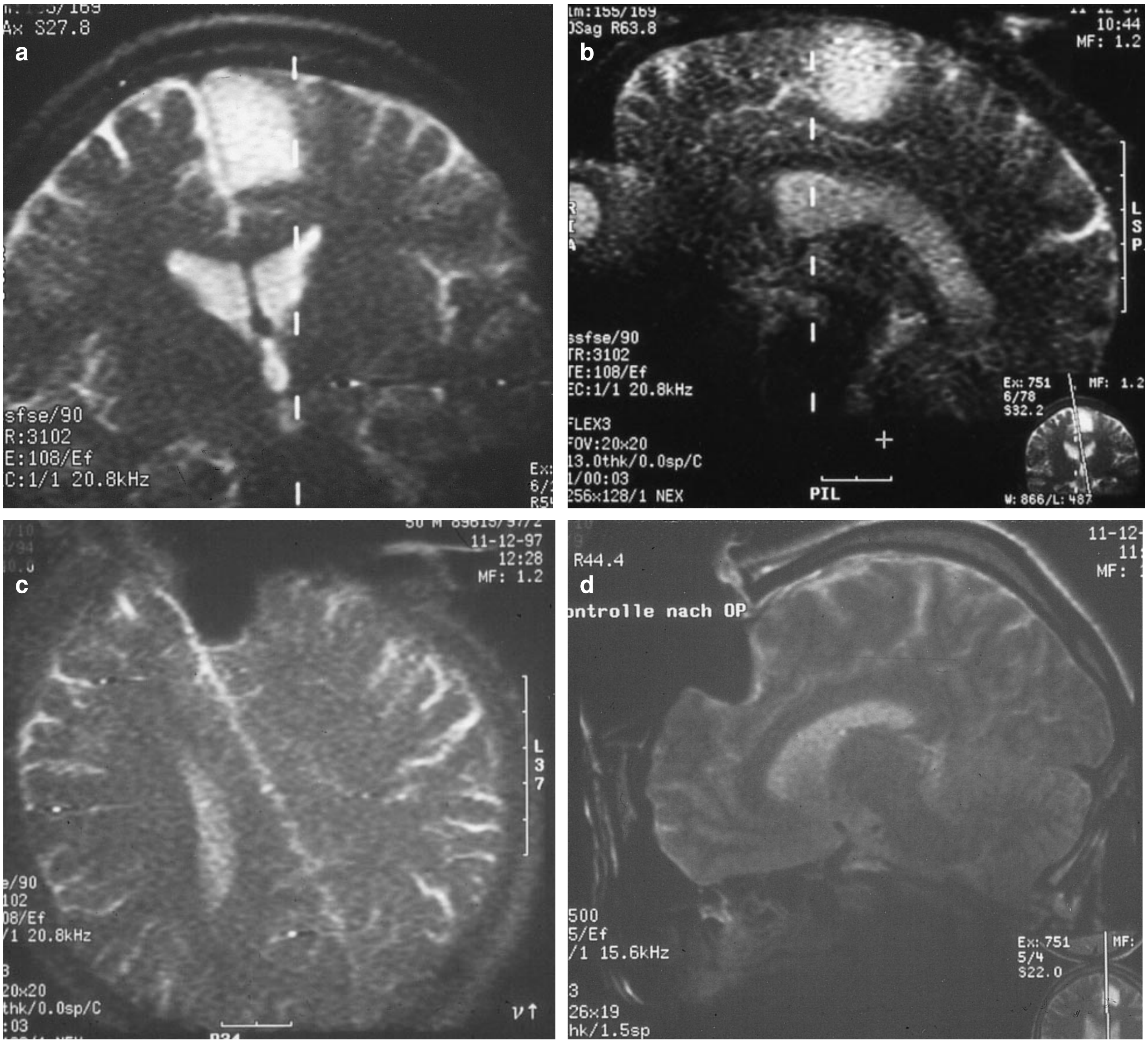

Fig. 5. Interactive image guidance with the optical LED-tracking system in a patient with a low-grade astrocytoma. Marking of the lateral (coronal T2-weighted MR-image) (a) and anterior tumour border (saggital T2-weighted MR-image) (b) Intra-operative MRI was obtained to demonstrate complete tumour removal (c–d)

unit without neurological deteriotation due to this intra-operative complication.

Transsphenoidal Surgery for Pituitary Tumors

The first transsphenoidal procedure for the resection of a pituitary tumor was performed in September 1997. Subsequently, 7 additional transsphenoidal procedures have been performed in the interventional MRI, including 6 pituitary adenomas, 1 rhabdoid tumour and 1 chordoma. The approach and the transsphenoidal removal of the pituitary tumours were completely performed in the interventional MRI using non-magnetic surgical instruments and a titanium retractor. The retractor caused only small artifacts which did not influence the quality of MR imaging during the whole surgical procedure (Fig. 8).

Interstitial Laser Application

Imaging thermal changes may increase the safety and efficacy of focused interstitial laser therapy, radiofrequency ablation and cryotherapy [4, 12, 13, 19]. The first of three open minimal invasive laser hyperthermia treatments was performed in October 1997 using intraoperative MR imaging. MR imaging makes it possible

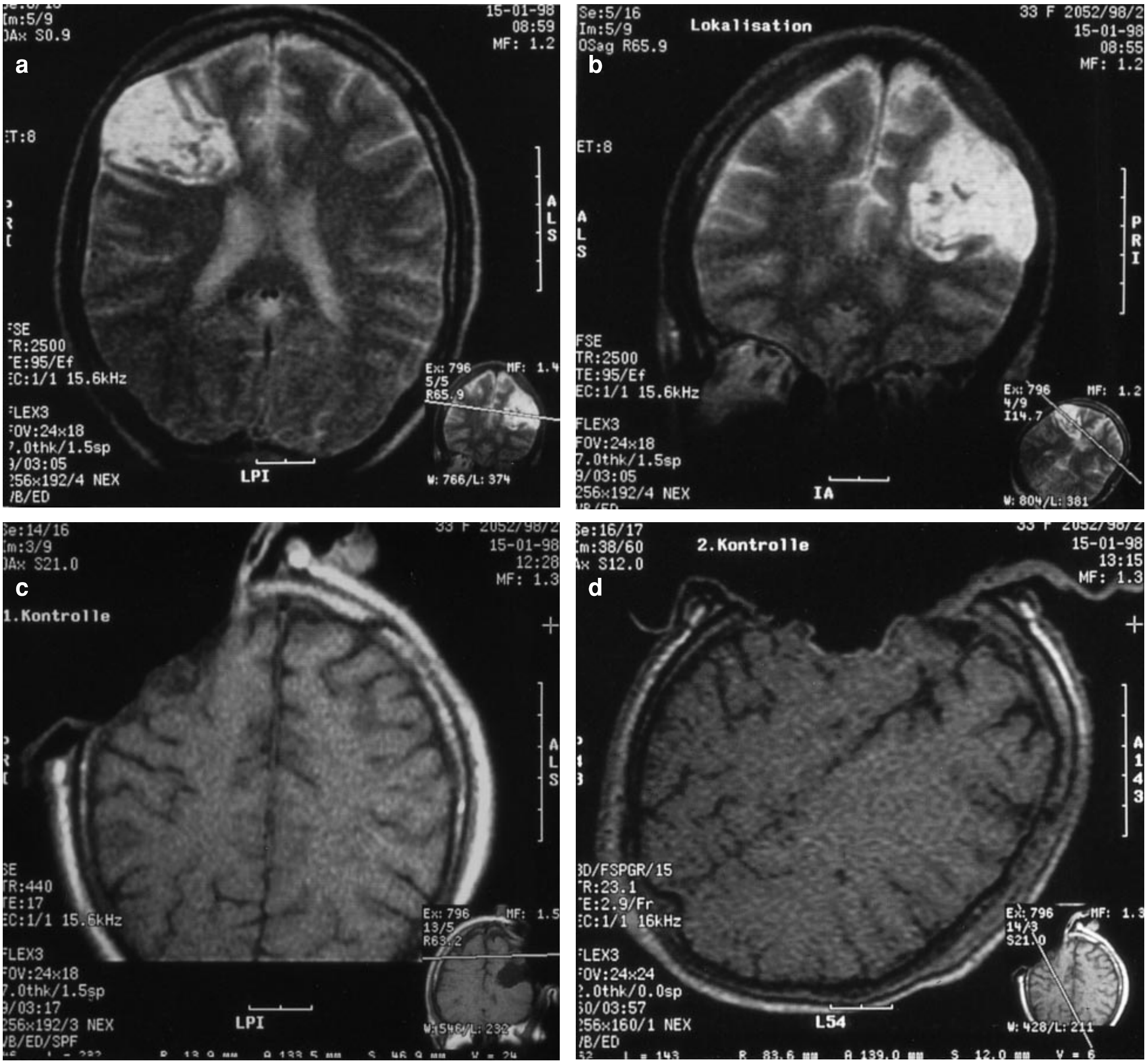

Fig. 6. MR images showing a craniotomy performed to remove a ganglioblastoma (WHOI) in a 34-year-old woman suffering from seizures. Images a and b (axial and coronal T2-weighted, without gadolineum) were obtained after positioning of the patient and coil fixation. Image c shows a small residual tumour, which was immediately removed (d)

to visualize temperature changes continuously during thermal ablative procedures. Using intra-operative MRI in combination with minimal invasive laser hyperthermia or cryotherapy enables the surgeon to detect the deposition of energy within the lesion while proceeding with the ablative procedure.

Discussion

The indications for surgery of suspected intracerebral lesions result from the development of optimised treatment strategies for some tumours and from the pressure to find such therapeutic concepts for other diseases. In recent years more and more minimal-invasive techniques for diagnostic brain biopsies and microneurosurgery of brain tumours and vascular lesions have been developed [6, 7, 19, 21, 25].

Because of its superior imaging modalities with optimal contrast differentiation for the detection of intracerebral lesions MRI can be regarded the ideal imaging system for the use of introperative image guidance in neurosugery.

However, because of the configuration of MR systems and the lack of MR compatible auxiliary equip-

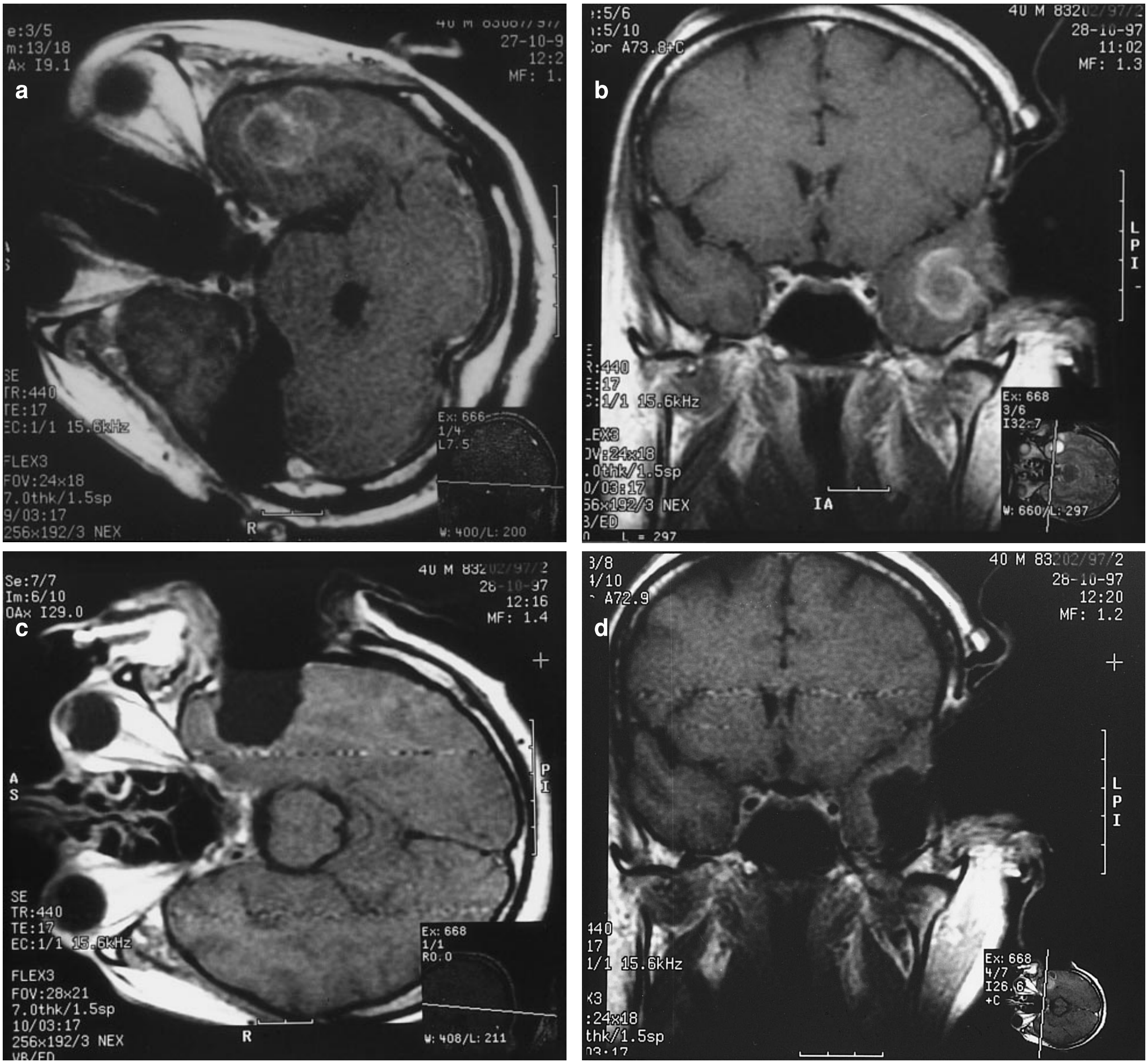

Fig. 7. Gadolineum enhanced T1-weighted MR-images of a 56-year-old patient with a left temporal glioblastoma (WHO IV), before (a–b) and after complete tumour removal (c–d). Images B–D were obtained after craniotomy

ment and surgical instruments, it was very difficult until now to perform neurosurgical procedures inside the MR. New perspectives resulted for MR guided and controlled procedures – which became even reality in some applications – from the development of so called open MR systems during the last five years [8, 14, 14–16, 26, 27].

The configuration of the "SIGNA SP" system allows an accurate, interactive MR guided targeting in several regions of the body [3, 14, 20, 24, 26, 27]. Because of good contrast between a lesion and the surrounding tissue in the brain and the lack of motion artefacts this method is also practicable for neurosurgical procedures [3, 14, 14].

In regard to intra-operative accuracy, no problem occured in the detection of lesions with a diameter of 0.8 cm or larger detected by a standard CT or MR examination. Despite the lower resolution and lower contrast compared to imaging with a conventional 1.5 T scanner all suspected lesions were visible on T1w or T2w images using the open system and the flexible transmit/receive coil.

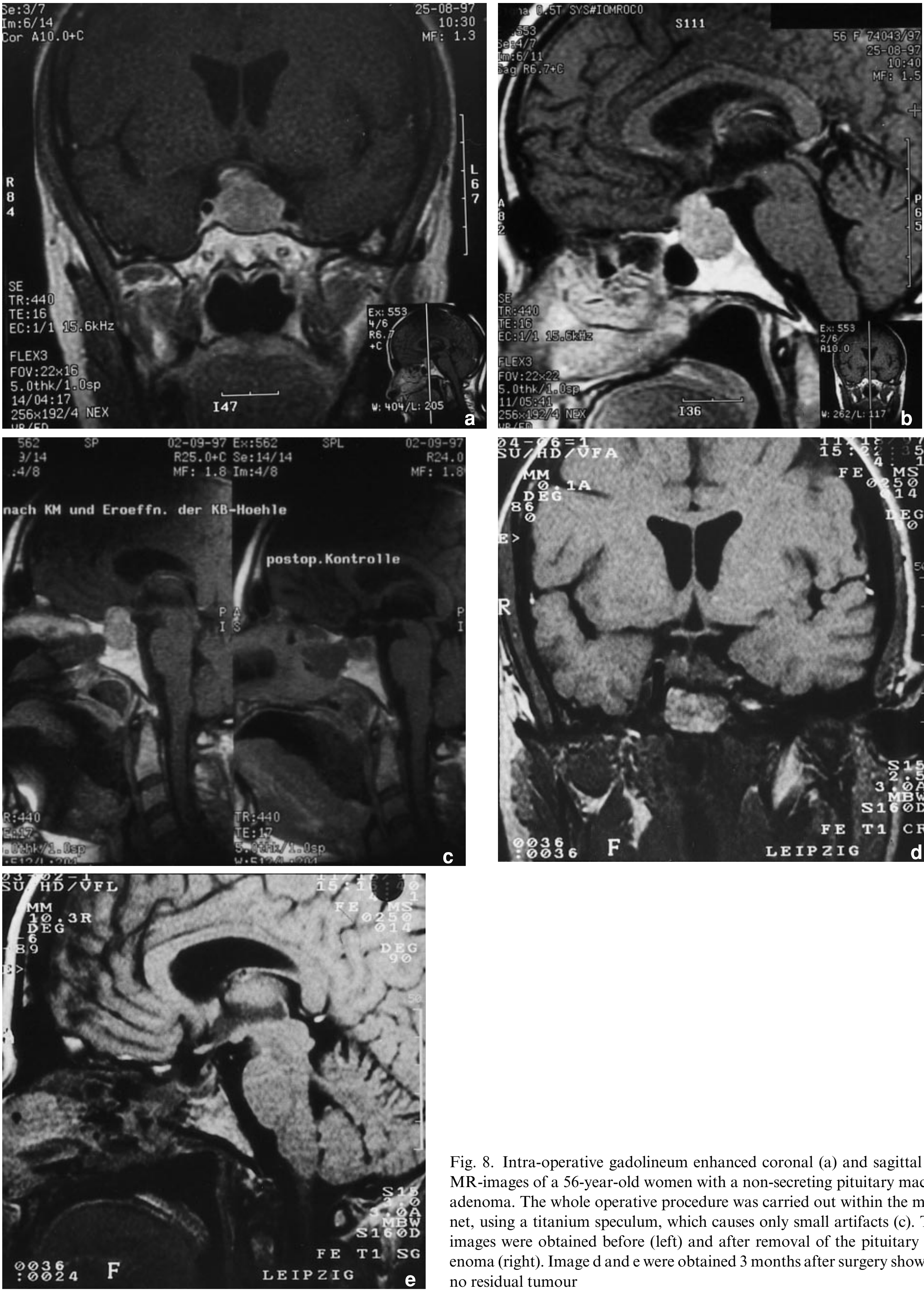

Fig. 8. Intra-operative gadolineum enhanced coronal (a) and sagittal (b) MR-images of a 56-year-old women with a non-secreting pituitary macroadenoma. The whole operative procedure was carried out within the magnet, using a titanium speculum, which causes only small artifacts (c). The images were obtained before (left) and after removal of the pituitary adenoma (right). Image d and e were obtained 3 months after surgery showing no residual tumour

Essential for a good image quality was the position of the patient and of the coil in relation to the homogeneous part of the magnetic field. It was necessary to achieve this in combination with a good access for the neurosurgeon. In every case we tried to position the patients head in a way that the lesions come near to the isocenter and simultaneous to the centre of the volume framed by the two coil loops.

The free hand use of the 3 LED-tracking handpiece in combination with the single slice gradient echo sequence (T1w or T2*w) in the continuous near real-time imaging mode was used for planning interactively the best location for the craniotomy. A helpful instrument for guiding the instrument exactly to the target area was a computer simulated virtual needle.

Nevertheless during the first procedures some problems arose which resulted from components of the MR system or the auxiliary equipment. They rendered the operation more difficult or prolonged the procedure. Another problem was the limited mobility of the holding device in the first prototype version. We had also difficulties with the targeting in cases of suspected lesions without any contrast enhancement and a blurred demarcation on native T1w images, e.g. low grade astrocytomas. These tumours were visible with fast T2w spin echo sequences. But neither with faster T2w spin echo sequences ("spotlite") nor with a T2*w gradient echo sequence it was possible to differentiate between the tumour and the surrounding oedema. With the prescribed gradient echo sequences in the continuous imaging mode the detection of lesions was very difficult. Therefore we carried out the tumour removal without interactive scanning in such cases. In our opinion a clear differentiation between tumour and surrounding structures also in near real-time images is of great importance for the result and accuracy of the surgery.

Immediate intra-operative monitoring can be also very helpful in the case of a complication due to the surgery, e.g. in case of a haemorrhage. If such an event is immediately recognised due to intra-operative imaging the neurosurgeon can deal with the problem e.g. by evacuating the haematoma within the magnet. In one patient suffering from a brain metastasis an epidural haematoma was recognized at the postoperative MRI after wound closure. The haematoma was evacuated and the result demonstrated by intra-operative MRI. The risk of clinical sequelae secondary to such a bleeding is lower [3].

In summary it was possible to introduce the interactive MR guided brain biopsy in the course of one year as a clinical routine method after getting experience in using the scanning and tracking systems and after development of some auxiliary equipment (holding device, surgical intruments, micoscope, special side cut needles for brain biopsies). In a second step microneurosurgical procedures, e.g. microsurgery of brain tumours or transphenoidal procedures, were performed entirely in the interventional MRI after the completion of MR compatible equipment. The whole procedure can be carried out in the vertical opened MR system. Intra-operative MRI provides near realtime images, which enable the surgeon to modify the preplanned approach during the actual surgery. The use of LED-based optical tracking of surgical instruments (e.g. needles, pointers, micosurgical instruments) in combination with the changes of MRI planes provides continous interactive feedback between the surgical manoeuvres and the corresponding images [23, 26].

It is still too early to define the role of interactive MR guided neurosurgical procedures in comparison with other established methods from the diagnostic, therapeutic and economic point of view. But it can already be concluded that the large and unique potential of intra-operative MRI in controlling minimal-invasive interstitial thermotherapies (laser, cryo, RF-ablation or focused ultrasound), tumour biopsies and microsurgical procedures,marks a significant advance in neurosurgery.

References

1. Apuzzo MLJ, Sabshin JK (1983) Computed tomographic guidance stereotaxis in the management of intracranial mass lesions. Neurosurgery 12: 277–285
2. Barnett GH, Kormos DW, Sator K, Weisenberger J (1993) Use of a frameless, armless stereotactic wand for brain tumor localization with two-dimensional and three-dimensional neuroimaging. Neurosurgery: 674–678
3. Black PM, Moriaty T, Alexander EA, Stieg P, Woodard EJ, Gleason L, Martin CH, Kikins R, Schwartz RB, Jolesz FA (1997) Development and implementation of intraoperative magnetic resonance imaging and its neurosurgical applications. Neurosurgery 41: 831–845
4. Bleier A, Jolesz FA, Cohen M, Weisskopf R (1991) Real-time magnetic imaging of laser heat deposition in tissue. Magn Res Med 21: 132–137
5. Bucholz RD, Smith KR, Henderson J (1993) Intraoperative localization using a three dimensional optical digitizer. Proc SPIE 1894: 312–322
6. Carter BS, Harsh GR (1996) Diagnosis of suspected intracranial metastases. Role of direct tissue examination. Neurosurg. Neurosurg Clin North Am 7: 425–433
7. Ebel H, Rust DS, Scheuerle A (1996) Value of stereotaxy in neurosurgery. Indications and analysis of results of 71 cases. Nervenarzt 67: 650–658

8. Friebe M, Grönemeyer D (1995) Der Kernspintomograf als Therapiegerät. Krankenhaus Technik 4: 56–62
9. Galloway RLL, Marcinuas RJ, Latimer JW (1991) The accuracies of four stereotactic frame systems: an independent assessment. Biomed Instrument Technol 25: 457–460
10. Guthrie BL, Adler JR (1995) Computer-assisted preoperative planning, interactive surgery, and frameless stereotaxy. Clin Neurosurg 38: 112–131
11. Heilbrun MP, Roberts TS, Apuzzo MLJ, Wells TH, Sabshin JK (1983) Preliminary experience with Brown-Roberts-Wells (BRW) computerized tomography stereotaxic guidance system. J Neurosurg 59: 217–222
12. Higuchi N, Bleier AR, Jolesz FA, Colucci VM, Morris JH (1992) MRI of the acute effects of interstitial neodynium: YAG laser on tissues. Invest Radiol 27: 814–821
13. Jolesz FA, Moore GJ, Mulkern RV, Bleier AR, Gonzales RG, Bowers JL, Metz KR, Higuchi N, Colucci VM (1989) Response to and control of destructive energy by magnetic resonance. Invest Radiol 24: 1024–1027
14. Kettenbach J, Silverman SG, Schwartz RB, Hsu L, Koskinen SK, Kikins R, Black PM, Jolesz FA (1997) Aufbau, klinische Eignung und Zukunftsaspekte eines 0,5-T-MR-Spezialsystems für den interventionellen Einsatz. Radiologe 37: 825–834
15. Lenz GW, Dewey C (1995) Interventional MRI. Electromedica 63: 41–45
16. Lufkin RB (1996) Interventional MR imaging. Radiology 197: 16–18
17. Marcinuas RJ, Galloway RL, Fitzpatrick JM (1992) A universal system for interactive image-directed neurosurgery. Stereotact Funct Neurosurg 58: 108–113
18. Internet Communication. Martin C, Alexander EA, Wong T, Schwartz R, Jolesz F, Black PM (1998) Anonymous surgical treatment of low-grade gliomas in the intraoperative magnetic resonance imager. Neurosurg Focus, pp article 8, 4. Anonymous
19. Matsumoto K, Tomita S, Higashi H, Nakagawa M, Adachi H, Tade E, Maeda Y, Ohmoto T (1995) Image guided stereotactic biopsy for brain tumors: experience of 71 cases. No Shinkei Geka 23: 897–903
20. Moriaty TM, Kikins R, Jolesz FA, Black PM, Alexander EA (1996) Magnetic resonance imaging therapy. Neurosurgery Clin North Am 7: 323–331
21. Moringlane JR, Voges M (1995) Real-time ultrasound imaging of cerebral lesions during "target point" stereotactic procedures through a burr hole. Acta Neurochir (Wien) 132: 134–137
22. Roberts DW, Strohbehn JW, Hatch JF, Murray W, Kettenberger H (1986) A frameless stereotaxic integration of computerized tomographic imaging and the operating microscope. J Neurosurg 65: 545–549
23. Schenk JF, Jolesz FA, Roemer PB, Cline HE, Lorensen WE, Kikins R, Silverman SG, Hardy CJ, Barber WD, Trifon Laskaris E, Dorri B, Newman RW (1995) Superconducting open configuration MRI system for image-guided therapy. Radiology 195: 805–814
24. Schmidt F, Schneider JP, Thiele J, Sorge O, Dietrich J (1997) Holding device for MR-guided biopsies. Fortschr Röntgenstr 166 177: 177
25. Scholz M, Schwechheimer K, Hardenack M, Heuser L, Harders AG (1996) MIN-biopsy of brain tumors: operative technique and histomorphological results. Minim Invasive Neurosurg 39: 12–16
26. Silverman SG Collick BD, Figueira MR, Khorasani R, Adams DF, Newman RW, Topulos GP, Jolesz FA (1995) Interactive MR-guided biopsy in an open-configuration MR imaging system. Radiology 197: 175
27. Steiner P, Schoenberger AW, Penner EA, Erhardt P, Debatin JF, von Schulthess GK, Kacl GM (1996) Interactive stereotaxic interventions in superconducting, open 0.5-Tesla MRI tomography. Fortschr Röntgenstr 165: 276–280
28. Watanabe E, Mayangi Y, Kosugi Y, Manaka S, Takakura K (1991) Open Surgery assisted by the neuronavigator: A stereotactic, articulated, sensitive arm. Neurosurgery 28: 792–800
29. Watanabe E, Watanabe T, Manaka S (1987) Three-dimensional digitizer (neuronavigator): New equipment of computed tomography-guided stereotactic surgery. Surg Neurol 27: 543–547
30. Zinreich JS, Tebo SA, Long DM, Brem H, Bryan RN, Mattox DE, Lowry MC, Van der Volk CA, Koch WM, Kennedy DW, Bryan RN (1993) Frameless stereotactic integration of CT imaging data: accuracy and initial applications. Radiology 188: 735–743

Comment

This is a very good paper about a very up to date problem and perspective in neurosurgery. The authors provide an important experience in this field; the images at this strength of field are the best I have seen so far; the description of their method, of their results is clear and convincing. They have achieved the painful task of having non-magnetic equipment designed and constructed. Their paper is one of the most convincing reports about MRI open field surgery and gets as close as possible to a routine procedure for Neurosurgery Teams.

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