Acta Neurochir (2002) [Suppl] 85: 121–125

Surgical Navigation in the Open MRI

A. Nabavi[1,3,4], **D. T. Gering**[4,5], **D. F. Kacher**[2], **I.-F. Talos**[3,4], **W. M. Wells**[4,5], **R. Kikinis**[2,4], **P. McL. Black**[3], and **F. A. Jolesz**[2]

[1] Department of Neurosurgery, University Kiel, Kiel Germany
[2] Department of Radiology, Brigham and Women's Hospital, Harvard Medical School, Boston, MA
[3] Department of Neurosurgery, Brigham and Women's Hospital, Harvard Medical School, Boston, MA
[4] Surgical Planning Laboratory, Brigham and Women's Hospital, Harvard Medical School, Boston, MA
[5] Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, MA

Summary

The introduction of MRI into neurosurgery has opened multiple avenues, but also introduced new challenges.

The open-configuration intraoperative MRI installed at the Brigham and Women's Hospital in 1996 has been used for more than 500 open craniotomies and beyond 100 biopsies. Furthermore the versatile applicability, employing the same principles, is evident by its frequent use in other areas of the body.

However, while intraoperative scanning in the SignaSP yielded unprecedented imaging during neurosurgical procedures their usage for navigation proved bulky and unhandy.

To be fully integrated into the procedure, acquisition and display of intraoperative data have to be dynamic and primarily driven by the surgeon performing the procedure. To use the benefits of computer-assisted navigation systems together with immediate availability of intraoperative imaging we developed a software package. This "3D Slicer" has been used routinely for biopsies and open craniotomies. The system is stable and reliable. Pre- and intraoperative data can be visualized to plan and perform surgery, as well as to accommodate for intraoperative deformations, "brain shift", by providing online data acquisition.

Keywords: Intraoperative MRI; neuronavigation; brain-shift; 3D Slicer.

Introduction

Computer-assisted Neuronavigation made high-resolution and multimodal presurgical imaging available for intraoperative guidance [8, 25, 32]. Relevant anatomic structures are identified and segmented, rendering a 3D representation of the patient's pathology. 3D rendering of 2D medical image information permits interactive analysis of lesions in their spatial relationship [17]. This data as well as the basic grayscales are transferred to the OR for navigation employing rigid body transformation of the presurgical data ("image space") to the patient ("physical space") in surgery. With computer assisted navigational tools, the patient's anatomy can be visualized as 2D or 3D representations in relationship to the position of tracked, hand-held instruments within the surgical field [25, 32]. Once surgery commences, the brain deforms, due to its non-rigid properties. This intraoperative deformation, "brain shift", causes increasing inconsistencies between presurgical data and intraoperative reality [5, 12, 24]. Therefore the accuracy of navigation systems diminishes with proceeding surgery (Fig. 1).

Various attempts to categorize "brain shift" in order to achieve a predictive algorithm have been published [5, 23]. But even with serial intraoperative MRI there are major difficulties in analyzing the large and dynamic variety of intraoperative brain deformations [7, 11, 19]. Although computational approaches represent a major research effort, their present accuracy is unable to compensate for "brain shift".

A more pragmatic approach, although limited to specialized centers, is to integrate computer assisted navigation systems into existing intraoperative imaging units to update data sets for navigation [15].

In this paper we will present the integration of an in-house developed software application package [9] into an open MRI system.

Material and Methods

Beginning in 1993 a vertical gap mid-field strength MRI system (0.5 Tesla, SignaSP) was developed in a collaborative effort by Gen-

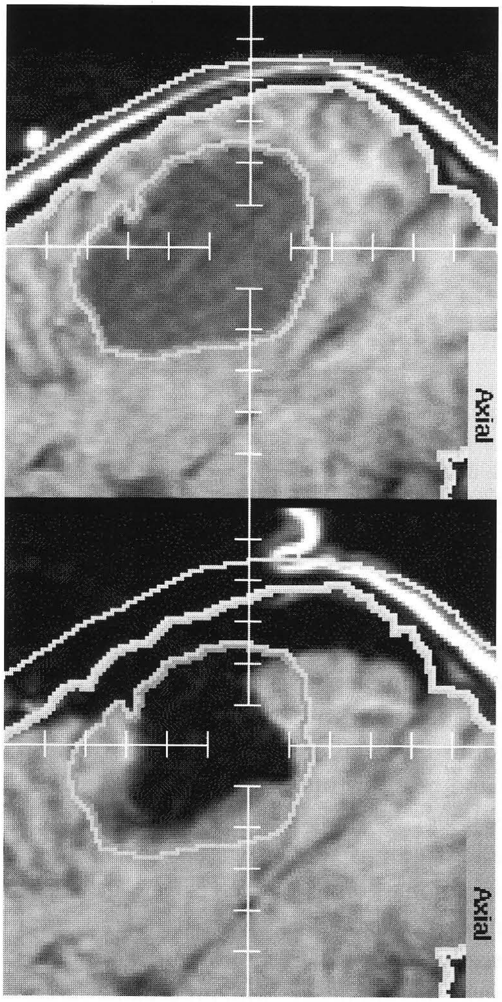

Fig. 1. Brain shift: The upper image shows the outlines/segmentation of an oligodendroglioma before craniotomy. The lower image shows the overlay of the same segmentation onto the corresponding post-resection image. Normal tissue has collapsed into the resection cavity. The hashmarks are at 1 cm intervals. The inaccuracy of presurgical imaging to describe intraoperative circumstances is evident

eral Electric (GE) Medical Systems (Milwaukee, WI) and the Brigham and Women's Hospital (BWH) [4, 13, 26, 27]. The scanner was designed to give access for open craniotomies while being able to acquire MRI studies during procedures without moving the patient. This BWH prototype has a 56 cm gap providing a spherical homogeneous (30 cm diameter) 0.5 T static field in the center of the open bore. This gap gives sufficient access for open surgery, although the surgeon's mobility is restricted. Multiple engineering and ergonomic challenges had to be overcome [14, 29]. Clinical reports have shown the versatile applicability of this approach in clinical routine [3, 4, 15, 16, 20, 27–29].

The scanner console and workstations for image-guidance and image processing are situated outside the shielded MR room. Neuroradiologist review the acquired images on this diagnostic console, communicating via intercom with surgeons within the MR who follow the images on LCD flat panel screens within the scanner bore.

To provide the user within the magnet with more control over the acquisition plane as needed for image guidance, a 3D-digitizer system (Flashpoint 5000, Image Guided Technologies, Boulder, CO) was installed as an integral part of the SignaSP. It consists of the same components as optical frameless stereotactic neuronavigation systems for the conventional OR, including three charge-coupled device (CCD) cameras and a locator with infrared light emitting diodes (LEDs) [3, 9, 26–29]. The cameras are integrated into a rail running between the two cryostats, directly above the surgical field. The locator position and orientation are updated at a rate of 10 Hz within the surgical field. The coordinates are calculated by a workstation (Sun Microsystems, Mountain View, CA). These coordinates can be sent to the scanner and used interactively to define an imaging plane. Depending on the elected pulse-sequence an image is updated within 3–24 seconds. After adjustments the scanner needs the allotted time, to create an image. The trajectory has to remain in the same plane for the duration of the scan. If the locator is moved during the acquisition, a new plane is automatically defined, blurring the acquired image. Used routinely for biopsy procedures, the optical navigation system can be similarly utilized to position catheter or needles (e.g. for cyst evaluation or drainage or to place thermal ablation probes).

Although the combination of the Flashpoint system with the SignaSP was essential for near real time guidance, it proved to be cumbersome and time-consuming to acquire the single images consecutively. Particularly in craniotomies, probing the cavity for residual lesion with this technique was too time-consuming and the system too inflexible for interactive usage. Once these shortcomings were discernible, the need for navigation software, which would yield interactive viewing of the imaging volume, while providing adequate interactive speed to be applicable for open surgery, became apparent.

The 3D Slicer, is an in-house developed software application [9], which integrates presurgical planning, 3D visualization and computer-assisted navigation with updated intraoperative images. The multiple functions provide capabilities for image editing, model generation and registration of multimodal presurgical (MRI, CT, SPECT, phase contrast MR Angiography, functional MRI) and intraoperative studies. The 3D Slicer has a modular, extendable design. It was developed based on the OpenGL graphics library using the Visualization Toolkit (VTK) for processing, and the Tcl/Tk scripting language for the graphical user interface.

The SignaSP console and imaging workstation are connected (TC/IP) to a visualization workstation (Ultra 30, Sun Microsystems, Mountain View, CA) running the 3D Slicer. The locator position is transferred to this workstation. Whenever the locator's position or orientation changes, the server sends the new data.

As soon as the updated intraoperative scans are acquired, they are transferred to the workstation and loaded into the Slicer. Since the patient has not moved between image acquisition and navigation, the image coordinates ("image space") correlate with the patient ("physical space"), without registration. The surgeon investigates the surgical field immediately using the locator. The corresponding updated image is displayed on the in-bore monitor with a virtual locator-representation in a user-specified plane. This enables the surgeon to identify structures in the field and correlate them to the image. Similarly he can scroll through the images, selecting his region of interest. Furthermore the plane of view can be arbitrarily changed, according to the angle of the locator in space, thus yielding axial, sagittal, coronal or arbitrary planes in the direction of the probe.

Results

The in-house developed 3D Slicer has become the visualization platform for medical image processing, image fusion, 3D Visualization and intraoperative navigation at the Surgical Planning Laboratory. The software has proven stable and versatile.

During the first two years the 3D Slicer has been used for biopsies (n = 10) and open craniotomies (n = 60) for various pathologies.

The preparations are alike for biopsies and open craniotomies. After the patient is positioned and the head rigidly fixed with a carbon fiber Mayfield three-point fixation clamp, a flexible MRI-surface coil is applied to the region. A 3D-volume scan of the patient's head is acquired. This scan is transferred to the workstation running our navigation software. Presurgical data can be aligned (image fusion using Maximization of mutual information MMI [33]) to this volume data set, and used for trajectory and approach planning. As the localizer is moved within the surgical field, the computer reformats these slices according to the detected position. The surgeon uses this tool to scroll through the image volume, and define the best approach.

For MRI-guided biopsies (Fig. 2) the intraprocedural MRI enables precise targeting and verification of the sample site [2, 18]. Of course avoidance respectively early detection of complications is a major issue, particularly in deep-seated lesions. The volumetric scan is uploaded into the 3D Slicer. This provides full spatial orientation with fast computer graphics to define entry point and trajectory interactively. The Slicer's virtual tip is used to explore the suggested needle path. Subsequently a burr hole is placed at the specified location. The trajectory is verified and the localizer fixed in this position. While slowly advancing the probe to the set depth, we acquire near real time scans, to rule out unnoticed deflection. Once in the target area the needle position within the signal abnormality can be confirmed additionally with conventional 2D scans, and subsequently the biopsies taken. If indicated a laser fiber can be introduced for thermal ablation of the targeted region. After withdrawing the needle, control scans are acquired, to rule out complications.

In MRI-guided craniotomies (Fig. 3), the Slicer is used more frequently throughout the procedure. Initial planning can be done, using presurgical data, registered to the positioned patient. After craniotomy images are acquired on demand. Generally updated imaging is requested in light of significant deformation and during successive resection stages. These new images, representing the current situation are loaded into the 3D Slicer for navigation. Particularly in the final

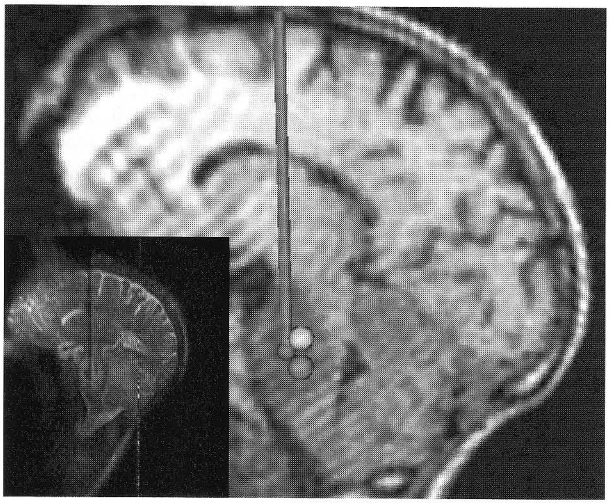

Fig. 2. Biopsies: The large image shows the Slicer display, as shown on the in-bore monitor. The surgeon is investigating various paths to the brainstem lesion. The pointer is set to a virtual depth. Potential target regions have been indicated (dots). Once the trajectory has been chosen, the needle is advanced (inlay) and the biopsy taken (note signal void at the biopsy site; a side-biting needle was used)

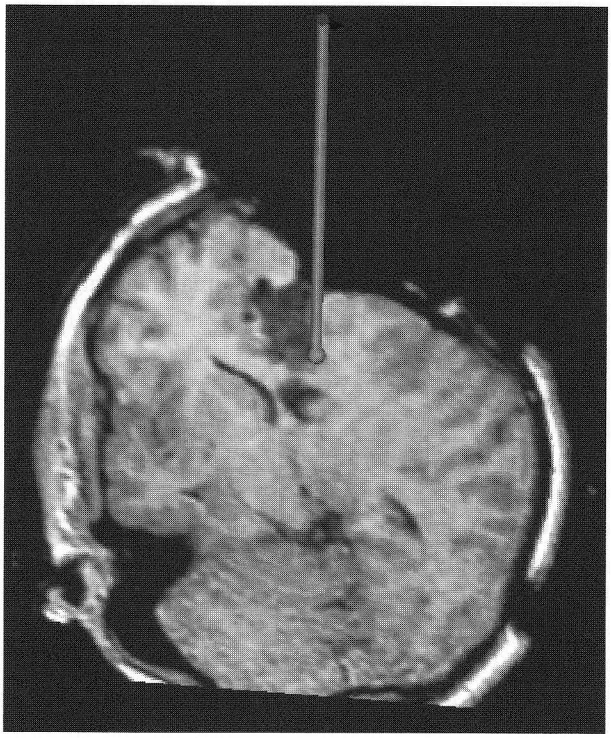

Fig. 3. Open craniotomy: After resection of a frontal oligodendroglioma the resection cavity is probed for residual lesion. The pointer is used to visualize the entire resection cavity on the in-bore monitor. This virtual pointer represents a real pointer in the surgeon's hand. Note the deformation, which would render presurgical images useless

stages of the procedure this alternation of resection and navigation with updated imaging, allowed not only the visualization of residual lesion, but also the precise localization and removal. Particularly in the vicinity of eloquent areas resection is controlled more frequently. Potentially even more important, the resection is stopped, when eloquent areas are endangered.

Discussion

Computer-assisted surgery was introduced to guide neurosurgical interventions [5, 17, 25, 32]. Nevertheless, intraoperative changes result in stereotactic inaccuracies. Various promising approaches to characterize and compensate for these changes were investigated. However, at present there is no alternative to intraoperatively updated images.

Among intraoperative imaging modalities, MRI has the highest resolution and sensitivity to detect residual tumor [3, 6, 10, 13, 21, 22, 27, 28, 30, 31, 34]. As our goal is to achieve a gross total tumor resection [1], identified as detectable signal abnormality, while respecting functional areas, frequent updates with high-resolution imaging yield the necessary information.

Various groups have combined commercially available software and navigation systems with images acquired in a MRI. Nimsky and Wirtz [22, 34] describe systems, which have separated imaging and surgical areas. Data transfer is necessary, as well as image to patient registration. Furthermore solutions that have separated areas for surgery and imaging, might be subject to inaccuracies due to deformations during the patient's transfer.

Our observations from serial intraoperative MRI [7, 19] demonstrated, that "brain-shift" is composed of diverse forces, magnifying and sometimes neutralizing each other. It is important to recognize the dynamic character of intraoperative deformations. We have observed meaningful changes within 30 minutes and less, which might have been missed by sporadic intraoperative imaging [22, 30, 34]. Therefore frequent intraoperative update is warranted to detect changes which might influence surgical decision making. The regularity of these updates depends on the surgical necessity to successfully conclude the operation in a timely fashion.

Our in-house developed software, the 3D Slicer is a platform for surgical planning and intraoperative, interactive image guidance. It was developed to complement the open-configuration MRI (SignaSP), which provides intraoperative imaging. Since "image space" and "physical space" are identical, time-consuming registration is unnecessary.

This integrated system has shown its benefit for updated navigation in neurosurgery.

Conclusion

Intraoperative Imaging is a great advance in Neurosurgery. To fully exploit the capacity of this new technology we developed a software application, the 3D Slicer for computer-assisted navigation. This integrated system enables the surgeon, to acquire and use near-real-time intraoperative images interactively, with all the advantages and high speed of computer-graphics.

References

1. Albert FK, Forsting M, Sartor K, Adams HP, Kunze S (1994) Early postoperative magnetic resonance imaging after resection of malignant glioma: objective evaluation of residual tumor and its influence on regrowth and prognosis. Neurosurgery 34: 45–60
2. Bernays RL, Kollias SS, Khan N, Romanowski B, Yonekawa Y (2000) A new artifact-free device for frameless, magnetic resonance imaging-guided stereotactic procedures. Neurosurgery 46: 112–116
3. Black PM, Alexander E 3rd, Martin C, Moriarty T, Nabavi A, Wong TZ, Schwartz RB, Jolesz F (1999) Craniotomy for tumor treatment in an intraoperative magnetic resonance imaging unit. Neurosurgery 45: 423–431
4. Black PM, Moriarty T, Alexander E 3rd, Stieg P, Woodard EJ, Gleason PL, Martin CH, Kikinis R, Schwartz RB, Jolesz FA (1997) Development and implementation of intraoperative magnetic resonance imaging and its neurosurgical applications. Neurosurgery 41: 831–842
5. Bucholz RD, Yeh DD, Trobaugh JW, McDurmont LL, Sturm C, Baumann C, Henderson JM, Levy A, Kressman P (1997) The correction of stereotactic inaccuracy caused by brain shift using an intraoperative ultrasound device. CVRMed-MRCAS 459–466
6. Fahlbusch R, Ganslandt O, Nimsky C (2000) Intraoperative imaging with open magnetic resonance imaging and neuronavigation. Childs Nerv Syst 16: 829–831
7. Ferrant M, Nabavi A, Macq B, Jolesz FA, Kikinis R, Warfield SK (2001) Registration of 3-D intraoperative MR images of the brain using a finite-element biomechanical model. IEEE Trans Med Imaging 20: 1384–1397
8. Galloway Jr RL (1998) Frameless stereotactic systems. In: Gildenberg PL, Tasker RR (eds) Textbook on stereotactic and functional neurosurgery. McGraw-Hill, New York, pp 178–182
9. Gering DT, Nabavi A, Kikinis R, Hata N, O'Donnell LJ, Grimson WE, Jolesz FA, Black PM, Wells WM 3rd (2001) An integrated visualization system for surgical planning and guid-

ance using image fusion and an open MR. J Magn Reson Imaging 13: 967–975

10. Hall WA, Martin AJ, Liu H, Pozza CH, Casey SO, Michel E, Nussbaum ES, Maxwell RE, Truwit CL (1998) High-field strength interventional magnetic resonance imaging for pediatric neurosurgery. Pediatr Neurosurg 29: 253–259
11. Hata N, Nabavi A, Wells WM, Warfield SK, Kikinis R, Black PM, Jolesz FA (2000) Three-dimensional optical flow method for measurement of volumetric brain deformation from intraoperative MR images. J Comput Assist Tomogr 24: 531–538
12. Hill DL, Maurer CR Jr, Maciunas RJ, Barwise JA, Fitzpatrick JM, Wang MY (1998) Measurement of intraoperative brain surface deformation under a craniotomy. Neurosurgery 43: 514–526
13. Jolesz FA (1998) Interventional and intraoperative MRI: a general overview of the field. J Magn Reson Imaging 8: 3–7
14. Jolesz FA, Morrison PR, Koran SJ, Kelley RJ, Hushek SG, Newman RW, Fried MP, Melzer A, Seibel RM, Jalahej H (1998) Compatible instrumentation for intraoperative MRI: expanding resources. J Magn Reson Imaging 8: 8–11
15. Jolesz FA, Nabavi A, Kikinis R (2001) Integration of interventional MRI with computer-assisted surgery. J Magn Reson Imaging 13: 69–77
16. Jolesz FA, Young IR (1998) Interventional MR: techniques and clinical experience. Springer, Berlin Heidelberg New York Tokyo
17. Kikinis R, Gleason PL, Moriarty TM, Moore MR, Alexander E, Stieg PE, Matsumae M, Lorensen WE, Cline HE, Black PM, Jolesz FA (1996) Computer-assisted interactive three-dimensional planning for neurosurgical procedures. Neurosurgery 38: 640–649
18. Moriarty TM, Quinones-Hinojosa A, Larson PS, Alexander E, Gleason PL, Schwartz RB, Jolesz FA, Black PM (2000) Frameless stereotactic neurosurgery using intraoperative magnetic resonance imaging: stereotactic brain biopsy. Neurosurgery 47: 1138–1145
19. Nabavi A, Black PM, Gering DT, Westin CF, Mehta V, Pergolizzi RS Jr, Ferrant M, Warfield SK, Hata N, Schwartz RB, Wells WM 3rd, Kikinis R, Jolesz FA (2001) Serial intraoperative magnetic resonance imaging of brain shift. Neurosurgery 48: 787–797
20. Nabavi A, Mamisch CT, Gering DT, Kacher DF, Pergolizzi RS, Wells III WM, Kikinis R, Black PM, Jolesz FA (2000) Image-guided therapy and intraoperative MRI in neurosurgery. Min Invas Ther & Allied Technol 9: 277–286
21. Nimsky C, Ganslandt O, Cerny S, Hastreiter P, Greiner G, Fahlbusch R (2000) Quantification of, visualization of, and compensation for brain shift using intraoperative magnetic resonance imaging. Neurosurgery 47: 1070–1079
22. Nimsky C, Ganslandt O, Kober H, Buchfelder M, Fahlbusch R (2001) Intraoperative magnetic resonance imaging combined with neuronavigation: a new concept. Neurosurgery 48: 1082–1089
23. Paulsen KD, Miga MI, Kennedy FE, Hoopes PJ, Hartov A, Roberts DW (1999) A computational model for tracking subsurface tissue deformation during stereotactic neurosurgery. IEEE Trans Biomed Eng 46: 213–225
24. Roberts DW, Hartov A, Kennedy FE, Miga MI, Paulsen KD (1998) Intraoperative brain shift and deformation: a quantitative analysis of cortical displacement in 28 cases. Neurosurgery 43: 749–758
25. 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
26. Schenck JF, Jolesz FA, Roemer PB, Cline HE, Lorensen WE, Kikinis R, Silverman SG, Hardy CJ, Barber WD, Laskaris ET *et al* (1995) Superconducting open-configuration MR imaging system for image-guided therapy. Radiology 195: 805–814
27. Schwartz RB, Hsu L, Wong TZ, Kacher DF, Zamani AA, Black PM, Alexander E 3rd, Stieg PE, Moriarty TM, Martin CA, Kikinis R, Jolesz FA (1999) Intraoperative MR imaging guidance for intracranial neurosurgery: experience with the first 200 cases. Radiology 211: 477–488
28. Seifert V, Zimmermann M, Trantakis C, Vitzthum HE, Kuhnel K, Raabe A, Bootz F, Schneider JP, Schmidt F, Dietrich J (1999) Open MRI-guided neurosurgery. Acta Neurochir (Wien) 141: 455–464
29. Silverman SG, Jolesz FA, Newman RW, Morrison PR, Kanan AR, Kikinis R, Schwartz RB, Hsu L, Koran SJ, Topulos GP (1997) Design and implementation of an interventional MR imaging suite. AJR Am J Roentgenol 168: 1465–1471
30. Steinmeier R, Fahlbusch R, Ganslandt O, Nimsky C, Buchfelder M, Kaus M, Heigl T, Lenz G, Kuth R, Huk W (1998) Intraoperative magnetic resonance imaging with the magnetom open scanner: concepts, neurosurgical indications, and procedures: a preliminary report. Neurosurgery 43: 739–747
31. Tronnier VM, Wirtz CR, Knauth M, Lenz G, Pastyr O, Bonsanto MM, Albert FK, Kuth R, Staubert A, Schlegel W, Sartor K, Kunze S (1997) Intraoperative diagnostic and interventional magnetic resonance imaging in neurosurgery [see comments]. Neurosurgery 40: 891–900
32. Watanabe E, Watanabe T, Manaka S, Mayanagi Y, Takakura K (1987) Three-dimensional digitizer (neuronavigator): new equipment for computed tomography-guided stereotaxic surgery. Surg Neurol 27: 543–547
33. Wells WM 3rd, Viola P, Atsumi H, Nakajima S, Kikinis R (1996) Multi-modal volume registration by maximization of mutual information. Med Image Anal 1: 35–51
34. Wirtz CR, Tronnier VM, Bonsanto MM, Knauth M, Staubert A, Albert FK, Kunze S (1997) Image-guided neurosurgery with intraoperative MRI: update of frameless stereotaxy and radicality control. Stereotact Funct Neurosurg 68: 39–43

Correspondence: Arya Nabavi, M.D., Department of Neurosurgery Kiel, Weimarerstr. 8, 24106 Kiel, Germany.