Neurosurg Focus 4 (4):Article 7, 1998

Three-dimensional image reconstruction for low-grade glioma surgery

Alexandra Chabrierie, M.S., Fatma Ozlen, M.D., Shin Nakajima, M.D., Michael E. Leventon, S.M., Hideki Atsumi, M.D., Eric Grimson, Ph.D., Ferenc Jolesz, M.D., Ron Kikinis, M.D., and Peter McL. Black, M.D., Ph.D.

Surgical Planning Laboratory, Department of Radiology and Division of Neurosurgery, Brigham and Women's Hospital, Children's Hospital, Harvard Medical School, Boston, Massachusetts; and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts

Three-dimensional image reconstruction for preoperative surgical planning and intraoperative navigation for the resection of low-grade gliomas was performed in 20 patients. Thirteen of these surgeries were performed while the patient received a local anesthetic to allow for cortical mapping. Ninety percent of the patients were functionally intact postoperatively. The authors propose that the combination of the three-dimensional image reconstruction and surgical navigation, in conjunction with intraoperative cortical mapping, provides an additional means for surgeons to improve the safety and precision of the procedures.

Key Words * low-grade glioma * three-dimensional reconstruction * navigation

Diagnostic imaging tools such as magnetic resonance (MR) imaging are useful in predicting tumor location, volume, and histological composition. The different MR modalities that may be used for assessment include T₁- and T₂-weighted images, MR angiograms, and functional MR imaging: all of these help to complete the initial diagnosis and aid planning of the surgical approach and subsequent patient management. The increased use of three-dimensional (3-D) image reconstruction methods[1,15,17,18,22,23,27] and surgical navigators[2,3,8,12,16,26,30-32] has resulted in a substantial changes in the practice of neurosurgery. We have developed a protocol for the use of 3-D reconstructions that combines these modalities into one comprehensive model, which is then used for surgical planning and intraoperative navigation. Intraoperative navigation is performed using a frameless stereotactic LED-based surgical navigator.[20] The 3-D image reconstruction method allows the surgeon to view all other neighboring cortical structures and provides a useful tool for planning the surgical approach and accurately assessing the extent of the tumor margins. The subsequent use of these reconstructions for intraoperative surgical guidance provides a comprehensive representation of the patient's brain that integrates anatomical and functional information for the optimization of both extent of tumor resection and patient safety.

Although the role of surgery in the treatment of low-grade gliomas remains controversial, recent

retrospective studies in which the effects of total and subtotal resections have been analyzed suggest that extended survival may be achieved with extensive surgical resection.[14,19,24,28,33] It has also been reported that the high risk of recurrence, either as a low-grade or higher-grade lesion, is reduced when less residual tumor is present after surgery.[4] Although it is necessary to maximize tumor resection, it is also imperative to maximize resection safety, thereby minimizing the risk of postoperative neurological deficits. Consequently, it is necessary to gain a firm understanding of the anatomical and functional architecture surrounding the lesion, which becomes less evident because precise information on the location of motor, sensory, speech, naming and visual cortices is not readily available when using conventional imaging techniques. These features are highly variable among patients. As a result, intraoperative cortical stimulation and mapping remains the most valid indicator of function.[5,6]

The ability to integrate the anatomical information provided by the 3-D image reconstruction with the functional data from intraoperative cortical stimulation produces a useful resource for surgeons. Twenty patients in whom a low-grade glioma was resected by using 3-D navigation were studied retrospectively.

CLINICAL MATERIAL AND METHODS

Patient Selection

Twenty patients (12 males and eight females) were selected retrospectively based on the results of postoperative histopathological findings. The patient ages ranged from 13 to 50 years old.

Three-Dimensional Image Reconstruction Data

A specific protocol for 3-D image reconstruction was created. The MR images were originally acquired in a series of 124 postcontrast spoiled gradient recalled acquisition (SPGR) slices. Each slice was 1.5 mm thick with 256 X 256 matrix in a 240 X 240-field of view (FOV) and was obtained using a 1.5 tesla superconducting MR imaging system (Signa; GE Medical Systems, Milwaukee, WI). Four more sequences were obtained including sagittal T₁-weighted spin-echo images, axial T₂-weighted spin-echo images, axial T₁-weighted spin-echo images, and 3-D phase-contrast MR angiograms. The MR angiogram (256 X 256 matrix in a 200 X 240-mm FOV) is obtained in either the sagittal or axial plane. The velocity encoding is chosen specifically for each case: 60 cm/second for the arterial structures and 20 cm/second for venous structures. Raw MR image data are digitally transferred to a workstation (Ultra SPARC Station; Sun Microsystems, Inc., Mountain View, CA) at the Surgical Planning Lab via electronic network.

Image Processing

Each image is initially filtered by means of anisotropic diffusion.[9] Each SPGR sequence is segmented by using signal intensities and voxel connectivity.[10,11] Each structure including skin, brain, ventricles, vessels and other relevant structures including the lesion are segmented by using the marching cubes algorithm and surface rendering.[10,11,13] The structures are then integrated in a single-model Creator3D (Sun Microsystems, Inc., Mountain View, CA) and displayed on a workstation (Sun) running the LAVA (Sun) program. The model can be rotated in any direction, and each structure may be rendered translucent or transparent.

Image Registration

To fuse the imaging information a coregistration method has been used routinely that combines SPGR

images with those obtained using MR angiography, proton density-, and T₁- and T₂-weighted images.[34] This method insures that a lesion that might be missed on one image will be revealed by another. These modalities may then be combined with computerized tomography scanning for bony structures and with single-photon emission computerized tomography data to increase the resources available to the surgeons both pre- and intraoperatively.

Intraoperative Navigation

Prior to surgery, a dynamic reference frame equipped with three LEDs (Image Guided Technologies, Inc.) is fixed next to the patient's head. An LED probe is used to record from a series of points on the patient's skin (Image Guided Technologies, Inc.). The information is tracked using an optical digitizer (Flashpoint 5000; Image Guided Technologies, Inc.). The points recorded in real space are then matched to the 3-D model in a two-stage process. An initial rough alignment is achieved by recording the real-space location of three points and then manually matching those points on the MR imaging model. This initial registration is refined by finding the optimal transformation that aligns all of the points on the skin surface of the model.[30] Following registration, the surgeon is asked to point to a known area on the patient using the LED probe to confirm correspondence among the patient and the 3-D model and MR imaging slices. During the surgery, the surgeon uses a sterile LED probe to point to any point on or inside the patient's brain. Any point may be recorded and displayed on the 3-D model by using an arrow or simple dot (see Fig. 1).

Fig. 1. Upper Left: Intraoperative photograph showing the exposed tumor following opening of the dura mater. The tip of the probe is shown on the left, pointing to the area that caused speech arrest during cortical stimulation. Upper Right: Three-dimensional reconstructed image of the patient's brain. The vessels are represented in blue, the ventricles in light blue, the precentral gyrus in purple, and the tumor in green. The red dot corresponds to the speech area. The white arrow represents the probe on the adjacent intraoperative image. Lower: Orthogonal MR slices and cross-hairs representing the probe position.

Cortical Stimulation

Cortical stimulation in cases in which the lesion was thought to be near eloquent cortical areas was performed according to the technique previously described.[5]

RESULTS

Twenty patients with low-grade gliomas underwent surgery in which 3-D image reconstruction and surgical navigation were used to aid the surgeon. There were 10 low-grade astrocytomas (Grades I, II), seven oligoastrocytomas (without anaplastic features), and three oligodendrogliomas. Thirteen patients underwent cortical mapping; of these seven underwent speech and motor mapping, two underwent motor mapping alone, one underwent speech mapping alone, and three underwent motor and sensory mapping. A subtotal resection was achieved in 31% of patients. Ninety percent of the patients exhibited no neurological deficits. One patient exhibited temporary left-sided weakness. Cortical mapping had represented the sensory cortex diffusely behind this patient's gross tumor. The weakness was thought to be due to swelling. One patient showed a mild, left-sided upper-extremity proprioceptive deficit that was due to a vascular accident on postoperative Day 1 (Tables 1-3).

TABLE 1 LIST OF PATIENTS WITH LOW-GRADE ASTROCYTOMAS IN WHOM 3D IMAGE RECONSTRUCTION AND INTRA- OPERATIVE NAVIGATION WERE PERFORMED					
Case No.	Sex, Age (yrs)	Cortical Mapping	Extent of Resection	Location of Tumor	Postop Neurological Deficits
1	M, 38	motor & speech	total	lt frontal	none
2	M, 50	motor & speech	total	rt temporal	none
3	M, 43	motor & speech	total	lt frontal	none
4	M, 37	motor & speech	total	rt frontal	none
5	M, 49	motor	subtotal	rt frontal	none
6	F, 27	speech & motor	total	lt frontal	none
7	M, 50	speech & motor	total	lt frontal	none
8	F, 49	none	total	lt frontal	none
9	F, 38	none	total	lt frontal	none
10	M, 42	speech & motor	subtotal	rt temporal	none

TABLE 2 LIST OF PATIENTS WITH OLIGOASTROCYTOMAS IN WHOM 3D IMAGE RECONSTRUCTION AND INTRAOPERATIVE NAVIGATION WERE PERFORMED					
Case No.	Sex, Age (yrs)	Cortical Mapping	Extent of Resection	Location of Tumor	Postop Neurological Deficits
1	M, 17	motor & sensory	total	rt parietal	none
2	F, 13	none	total	rt parietal	none
3	F, 37	motor & speech	total	lt temporal	none
4	M, 43	motor	total	rt temporal	none
5	F, 34	none	total	lt parietal	none
6	M, 39	speech & motor	total	lt frontal	none
7	F, 29	motor & sensory	total	rt parietal	mild, upper left extremity proprioceptive deficit

TABLE 3 LIST OF PATIENTS WITH OLIGODENDROGLIOMAS IN WHOM 3D IMAGE RECONSTRUCTION AND INTRAOPERATIVE NAVIGATION WERE PERFORMED					
Case No.	Sex, Age (yrs)	Cortical Mapping	Extent of Resection	Location of Tumor	Postop Neurological Deficits
1	M, 47	motor & speech	subtotal	lt parietal	none
2	F, 41	motor & sensory	total	rt parietal	none
3	M, 45	none	subtotal	rt frontal	temporary left-sided weakness

ILLUSTRATIVE CASE

This 38-year-old man presented with episodes of word-finding difficulties. Magnetic resonance imaging revealed a space-occupying lesion in the left frontal lobe that was consistent with a low-grade glioma. Three-dimensional image reconstruction was performed preoperatively and tumor and the precentral gyrus were visualized (Fig. 1). The patient underwent an awake left frontotemporal craniotomy with speech mapping. Intraoperative navigational guidance was used to assist in the resection of his glioma. When the dura was opened, slightly abnormal tissue could be identified, and it appeared to be just in front of Broca's area. The speech area was mapped out using the Ojemann bipolar stimulator (Radionics, Inc., Burlington, MA) and it was recorded on the 3-D model. The intraoperative navigator was used to localize the tumor for the craniotomy and resection. The tumor seemed to extend medially just underneath the speech area. The navigator was used to localize this area, which was then carefully resected without affecting the patient's speech. After administration of intravenous sedation, the patient was awake and conversant throughout the procedure. A total resection was achieved. The patient tolerated the operation well and was released in good condition.

DISCUSSION

Although the length of survival in patients initially diagnosed with low-grade gliomas has significantly increased during the past decade, the importance of radical resection in the enhancement of survival remains controversial.[21,25,29] However, significant evidence has been presented to support the theory that lower residual tumor volume retards the recurrence and malignant transformation of these tumors.[4,7]

We present a tool that enhances the efficiency of lesion localization and determination of its boundaries and provides functional data on the areas surrounding it. Several surgical challenges may be overcome by

using our technique. First, MR imaging data are normally presented in a two-dimensional format that requires the surgeon to mentally transform it into 3-D space and obviously requires a firm understanding of the anatomical architecture of the brain surrounding the lesion in 3-D space. Our 3-D image reconstructions provide an intuitive way for the surgeon to visualize the lesion, including its size, exact location, and effect on brain architecture. Cortical lesions, even if they do not cause a mass effect, often disrupt the brain's surface, therefore perturbing any functional assessment based on anatomy and increasing the risk of postoperative neurological deficits. Our surface-rendering method provides a detailed representation of the brain surface and thus gives valuable insight into the surgical strategy. Each gyrus and sulcus is reproduced, resulting in a reliable depiction of the brain based on the preoperative MR images. The ability to vary the opacity for each substructure including the skin and brain allows a thorough spatial understanding of the location of the lesion in relation to the whole head.

Safe resection of a tumor involves keeping the patient functionally intact. When lesions are located near eloquent cortex, cortical stimulation in the awake patient remains the most reliable method to guide safe resection.[5-7] The intraoperative navigator that we described allows any probed point to be recorded on the 3-D model and orthogonal MR slices.[20] The ability to track the Ojemann stimulator and record its position on the models and the MR images enables the surgeon to view the areas that are functionally relevant in relation to the tumor as well as to the rest of the brain. This complements the conventional technique of marking eloquent sites with sterile numbered tickets on the brain surface. The ability to record the stimulation results as markers on the 3-D model, which enables the surgeon to see them in the 3-D configuration of the lesion, provides a better correlation between the images and the operative field.

Additional benefits of 3-D image reconstruction include a better understanding of the effect of the lesion on the brain's anatomy. It also improves localization of the lesion for planning the incision, the craniotomy, and for resecting the tumor with minimal damage to the normal brain tissue.

Although these techniques facilitate the resection, they are not direct predictors of a patient's prognosis. This is especially true because the major cause of mortality in these patients is the malignant transformation of these tumors into high-grade gliomas.[7] Using the 3-D image reconstruction and intraoperative navigation techniques for the surgical management of patients with low-grade glioma helps guide the surgeon and therefore maximizes achievement of the surgical goal. However, the progression of tumor remains intrinsic to its cellular properties. A longer follow-up period and correlation of the extent of resection with a long-term survival will be needed to determine the advantages of these techniques on the overall management of patients.

Acknowledgments

The authors thank their colleagues for their help and support, in particular, Marianna Jakab, William Wells, Caryn Sefton, and Sheila Harney.

References

1. Aoki S, Sasaki Y, Machida T, et al: Cerebral aneurysms: detection and delineation using 3-D-CT angiography. **AJNR** 13:1115-1120, 1992
2. Barnett GH, Kormos DW, Steiner CP, et al: Intraoperative localization using an armless, frameless stereotactic wand. Technical note. **J Neurosurg** 78:510-514, 1993

3. Barnett GH, Kormos DW, Steiner CP, et al: Use of a frameless, armless stereotactic wand for brain tumor localization with two-dimensional and three-dimensional neuroimaging. **Neurosurgery** **33**:674-678, 1993
4. Berger MS, Deliganis AV, Dobbins J, et al: The effect of extent of resection on recurrence in patients with low grade cerebral hemisphere gliomas. **Cancer** **74**:1784-1791, 1994
5. Berger MS, Ojemann GA: Intraoperative brain mapping techniques in neuro-oncology. **Stereotact Funct Neurosurg** **58**:153-161, 1992
6. Berger MS, Ojemann GA, Lettich E: Neurophysiological monitoring during astrocytoma surgery. **Neurosurg Clin North Am** **1**:65-80, 1990
7. Berger MS, Rostomily RC: Low grade gliomas: functional mapping resection strategies, extent of resection, and outcome. **J Neurooncology** **34**:85-101, 1997
8. Black PM, Moriarty T, Alexander E III, et al: Development and implementation of intraoperative magnetic resonance imaging and its neurosurgical applications. **Neurosurgery** **41**:831-845, 1997
9. Cline HE, Dumoulin CL, Lorensen WE, et al: 3D reconstruction of the brain from magnetic resonance images using a connectivity algorithm. **Magn Reson Imaging** **5**:345-352, 1987
10. Cline HE, Lorensen WE, Kikinis R, et al: Three-dimensional segmentation of MR images of the head using probability and connectivity. **J Comput Assist Tomogr** **14**:1037-1045, 1990
11. Cline HE, Lorensen WE, Souza SP, et al: 3D surface rendered MR images of the brain and its vasculature. **J Comput Assist Tomogr** **15**:344-351, 1991
12. Golfinos JG, Fitzpatrick BC, Smith LR, et al: Clinical use of a frameless stereotactic arm: results of 325 cases. **J Neurosurg** **83**:197-205, 1995
13. Grimson WEL, Ettinger, GJ, White SJ, et al: An automatic registration method for frameless stereotaxy, image guided surgery, and enhanced reality visualization. **IEEE Trans Med Imaging** **15**:129-140, 1996
14. Guthrie BL, Laws ER Jr: Supratentorial low-grade gliomas. **Neurosurg Clin North Am** **1**:37-48, 1990
15. Hu XP, Tan KK, Levin DN, et al: Three-dimensional magnetic resonance images of the brain: application to neurosurgical planning. **J Neurosurg** **72**:433-440, 1990
16. Kato A, Yoshimine T, Hayakawa T, et al: A frameless, armless navigational system for computer-assisted neurosurgery. Technical note. **J Neurosurg** **74**:845-849, 1991
17. Kettenbach J, Jolesz FA, Kikinis R, et al: Surgical planning laboratory: a new challenge for radiology? in Lemke HU, Vannier MW, Inamura K (eds): **Computer Assisted Radiology and Surgery**. Amsterdam: Elsevier, 1997, pp 855-860
18. Kikinis R, Gleason PL, Moriarty TM, et al: Computer-assisted interactive three-dimensional planning for neurosurgical procedures. **Neurosurgery** **38**:640-651, 1996
19. Laws ER Jr, Taylor WF, Clifton MB, et al: Neurosurgical management of low-grade astrocytomas of

the cerebral hemisphere. **J Neurosurg** 61:665-673, 1984

20. Leventon ME: **A Registration, Tracking and Visualization System for Image-Guided Surgery**. Thesis. Cambridge, MA: Massachusetts Institute of Technology, 1997
21. Medbery CA III, Straus KL, Steinberg SM, et al: Low-grade astrocytomas: treatment results and prognostic variables. **In J Radiat Oncol Biol Phys** 15:837-841, 1988
22. Nakajima S, Atsumi H, Bhalerao AH, et al: Computer-assisted surgical planning for cerebrovascular neurosurgery. **Neurosurgery** 41:403-410, 1997
23. Nakajima S, Atsumi H, Kikinis R, et al: Use of cortical surface vessel registration for image-guided neurosurgery. **Neurosurgery** 41:1201-1210, 1997
24. North CA, North RB, Epstein JA, et al: Low-grade cerebral astrocytomas. Survival and quality of life after radiation therapy. **Cancer** 66:6-14, 1990
25. Piepmeyer JM: Observations on the current treatment of low-grade astrocytic tumors of the cerebral hemispheres. **J Neurosurg** 67:177-181, 1987
26. Reinhardt HF, Horstmann GA, Gratzl O: Sonic stereometry in microsurgical procedures for deep-seated brain tumors and vascular malformations. **Neurosurgery** 32:51-57, 1993
27. Schwartz RB, Jones KM, Chernoff DM, et al: Common carotid artery bifurcation: evaluation with spiral CT. Work in progress. **Radiology** 185:513-519, 1992
28. Soffietti R, Chio A, Giordana MT, et al: Prognostic factors in well-differentiated cerebral astrocytomas in the adult. **Neurosurgery** 24:686-692, 1989
29. Steiger HJ, Markwalder RV, Seiler RW, et al: Early prognosis of supratentorial grade 2 astrocytomas in adult patients after resection or stereotactic biopsy. An analysis of 50 cases operated on between 1984 and 1988. **Acta Neurochir** 106:99-105, 1990
30. Tan KK, Grzeszczuk R, Levin DN, et al: A frameless stereotactic approach to neurosurgical planning based on retrospective patient-image registration. Technical note. **J Neurosurg** 79:296-303, 1993
31. Watanabe E, Mayanagi Y, Kosugi Y, et al: Open surgery assisted by the neuronavigator, a stereotactic, articulated, sensitive arm. **Neurosurgery** 28:792-800, 1991
32. Watanabe E, Watanabe T, Manaka S, et al: Three-dimensional digitizer (neuro-navigator): new equipment for computed tomography-guided stereotaxic surgery. **Surg Neurol** 27:543-547, 1987
33. Weir B, Grace M: The relative significance of factors affecting postoperative survival in astrocytomas, grades one and two. **Can J Neurol Sci** 3:47-50, 1976
34. Wells WM III, Viola P, Atsumi H, et al: Multi-modal volume registration by maximization of mutual information. **Med Image Analysis** 1:35-51, 1996

Manuscript received March 16, 1998.

Accepted in final form April 2, 1998.

This research was supported by National Institutes of Health Grants RO1 CA 46227-08, PO1 CA 67165-01A1, and PO1 AGO4953-14, National Science Foundation Grant BES 9631710, and Darpa F41624-96-2-0001. This research is also supported by the Boston Neurosurgical Foundation.

Address reprint requests to: Peter McL. Black, M.D., Ph.D., Division of Neurosurgery, Children's Hospital, 300 Longwood Avenue, Boston, Massachusetts 02115. email: pblack@bics.bwh.harvard.edu.