An Internet-Connected, Patient-Specific, Deformable Brain Atlas Integrated into a Surgical Navigation System

Armond L. Levy, Timothy J. Schaewe, Michael I. Miller, Kurt R. Smith, Abed M. Hammoud, Jaimie M. Henderson, Sarang Joshi, Kevin E. Mark, Christopher D. Sturm, Leslie L. McDurmont, Jr. and Richard D. Bucholz

Standard anatomic information, such as that contained in atlases, is usually based upon individual human specimens, and therefore it cannot account for structural variability between patients. Thus, utilizing atlas information regarding specific locations and dimensions of anatomic structures could be misleading or incorrect if applied, without complex mapping criteria, to specific patients. This shortcoming is particularly noteworthy in the case of neuroanatomy, where brain structures may be very small, and yet may vary proportionally greatly in size, location, or even existence.

The advent of the World Wide Web (WWW) has already begun to affect the practice of medicine, especially the technologically oriented field of neurosurgery. Incorporating the capabilities of the WWW into the operating room setting could permit such advances as intraoperative enrollment into multicenter protocols, remote consultation, and demonstration of surgical techniques.¹ Solutions to the need for patient-specific anatomic information could be greatly enhanced by the advent of informational sources on the WWW. Mapping of patient-specific anatomic structures, pertinent to a particular surgical procedure, to corresponding WWW pages, with real-time access in the operating room, is a powerful new application of this technologic capability.

We are developing a three-dimensional brain atlas that integrates seamlessly with our existing frameless stereotactic, surgical navigation system. This new atlas will address anatomic variability by utilizing an image deformation algorithm to tailor standard atlas views to each individual patient's radiologic brain studies. This system will enable several distinct advantages over current technology, including "virtual" visualization of patient brain structures as high-resolution photographic images, real-time stereolocation of the surgical act within this three-dimensional virtual image, and integration via the Internet of neuroscience knowledge with surgery (see ref. 1 for an extensive list of neurosurgically related WWW sites).

METHODS

Surgical Navigation System

We have previously developed and employed clinically an optically based frameless surgical navigation system (StealthStation, Surgical Navigation Technologies, Boulder, CO) marketed by Sofamor Danek Group of Memphis, TN.^{2,3} The system consists of a UNIX-based computer workstation (Silicon Graphics Inc, Mountain View, CA) and an infrared optical digitizer (Flashpoint 5000, Image Guided Technologies, Boulder, CO) to display position real-time on a high-resolution monitor. The digitizer uses a charge-coupled camera array suspended from the operating room ceiling to track light-emitting diodes attached to a rigid reference array mounted to a Mayfield head clamp. The position of surgical instruments, modified by the addition of light-emitting diodes, is determined in the coordinate system of the reference array (Fig 1).

Image Deformation

An accurate simple overlay of atlas images onto patient radiographs is impossible because of interpatient geometric anatomic variability.⁴ Therefore, the atlas image must be "deformed" to match each individual. A hierarchic algorithm unifying both landmark-based and intensity-based transformations was developed to address this issue.^{5,6} The algorithm creates iterative solutions of a system of elasticity-based partial differential equations (PDE), which are applied as vector fields to the coordinate system of the template (atlas) image.

From the Division of Neurosurgery, St. Louis University Medical Center, St. Louis, MO; IntellIX, LLC, Boulder, CO; Department of Electrical Engineering, Washington University, St. Louis, MO; and Surgical Navigation Technologies (Sofamor-Danek Group), Boulder, CO.

Address reprint requests to Richard D. Bucholz, MD, FACS, Division of Neurosurgery, St. Louis University Medical Center, St. Louis, MO.

*Copyright © 1997 by W.B. Saunders Company
0897-1889/97/1003-1079\$3.00/0*

Fig 1. The StealthStation. Left: Computer cart and monitor with camera array. Top right: surgical forceps with attached LEDs. Bottom right: LED-equipped reference array arc attached to Mayfield head clamp.

Landmarks and linear manifolds such as sulci are identified in the dataset to serve as manifolds by which the template and target (patient) images are coarsely registered. Next, the full volumetric data are addressed. Both the difference between template and target intensities, and a constraint maintaining the relative structural topology of the template volume, are considered. This constraint is modeled by PDEs derived by modeling elastic deformations. The final transformation is accomplished via a course-to-fine iterative solution of the model-based PDEs on the full volume.^{5,6}

The Atlas

Our atlas is based upon the Visible Human dataset.⁷ Brain structures of zero, one, two, and

three dimensions are segmented onto the three-dimensional photographic template. A "segmentation map" file results. This file is then accessed as a look-up table from which a unique brain structure results from each voxel in the dataset, permitting mutually exclusive, real-time linkage to the WWW site(s) relevant to the selected brain structure. Furthermore, this segmentation map file can undergo deformation along with its corresponding template images by application of the identical vector fields described previously.

All images are handled in standard Analyze (Biomedical Imaging Resource, Mayo Foundation, Rochester, MN) format, and they are imported directly into the surgical navigation system, which has been enhanced to handle the display of two

complete volumetric datasets. The deformed photographic atlas, carrying its full segmentation, can be superimposed upon the patient dataset in real-time, and it can be shaded in or out by variable blending. The navigational system is therefore able to not only communicate the position of the surgical instrument with respect to preoperative images but also to determine which brain structure is at the tip of the surgical instrument based on the segmented dataset.

The final element of this "living atlas" is the linkage of each segmented anatomic feature to a page in the WWW. As the segmentation map is deformed along with the cryostatic template, the WWW look-up table can also be effectively deformed. By embedding a browser within the surgical navigation system, the current location of the instrument is correlated with a Universal Resource Locator (URL) on the Internet, which can be displayed for review. For example, if the neurosurgeon "clicks" while an instrument is within the hippocampus, that structure is highlighted on the

superimposed deformed photograph and the patient's three-dimensionally reconstructed MR image; at the same time, the appropriate hippocampus URL is retrieved from the WWW (eg, <http://weber.u.washington.edu/~jamo/hippoweb/hippoweb.html>⁸). This brings a wealth of current neuroscience information into the operating room in a fashion relevant to the hippocampus, or to any addressed brain structure(s) in real-time (Fig 2).

Validation

To demonstrate and validate this atlas and its deformational techniques, we employed image datasets obtained from patients undergoing stereotactically guided radiofrequency lesions of the globus pallidus for Parkinson's disease, performed at St. Louis University Hospital. It has been established that lesions of the posteroventral pallidum can produce long-term alleviation of parkinsonian symptomatology.⁹ The stereotactic target was selected at a point level with the third ventricular floor, 2 to 3 mm anterior to the midcommisural

Fig 2. Interactive Display. The patient's hippocampus has been highlighted and selected, as by a surgical instrument; a corresponding WWW page is automatically brought up by the incorporated browser.

Fig 3. (A) Postoperative T1-weighted axial MRI of RF-ablation pallidotomy. Lesion is visible just above and to right of center of cross-hairs. **(B)** Predicted pallidotomy target deformed, registered, and superimposed on actual postoperative scan. Deformed target visible as small white mark in the center of the lesion. (Patient scans courtesy of J.M. Henderson, MD, Division of Neurosurgery, St. Louis University.)

point, 21 to 22 mm lateral to the midline,⁹ based upon a preoperative MR imaging dataset. MR imaging distortion, movement artifact, and other inaccuracies were corrected by intraoperative third

ventriculography¹⁰ to fine-adjust the target. Finally, low-voltage stimulation of the target area was performed to delineate and avoid critical bounding structures such as the optic tract, followed by

Fig. 3 (Cont'd).

high-frequency radiofrequency ablation of the target.

The validation experiment uses the atlas to generate the targets in an automated fashion. A 4-mm spheric target in the pallidum was segmented on the template, which was deformed as previously mentioned to match the patient's preoperative ($n = 9$) or postoperative ($n = 3$) volumetric MR imaging dataset. (Only patients in whom intraoperative physiologic or ventriculographic corrections in stereotactic localization were not necessary were included in the study.) In patients who had only subvolumetric postoperative scans, these datasets were surface-registered, using Analyze, to their corresponding preoperative scans. By applying the deformation vector fields to the segmented targets, the deformed targets could be overlayed onto the postoperative scans, enabling comparison of the automated target selection and the actual, stereotactically confirmed target, easily visible on a postoperative scan (Fig 3). The average distance from the centroid of the lesion to that of the predicted target was calculated in three axes (anteroposterior, medio-

lateral, and craniocaudal) and statistically analyzed.

RESULTS

Results are given as value $\pm$ standard deviation. The previously described distance in the volumetric postoperative datasets ($n = 3$) was 5.5 ± 1.6 mm. The distance in the subvolumetric datasets was 3.4 ± 1.1 mm; this difference was not significant. An example of the predicted target overlayed on the pallidotomy lesion is shown in Figure 3. There were no significant trends in the orientation of the error vectors; the summed vector components yielded a resultant vector of only 2.6 mm. There was also no significant difference in error vectors between left (4.0 ± 0.3 mm, $n = 4$) and right (4.0 ± 1.9 mm, $n = 7$) pallidotomy lesions.

Because of the nature of the acquisition of the Visible Human dataset, the corresponding MR image was not suitable for our deformation algorithm for several reasons: (1) the scan resolution is only 4 mm in the z dimension, which is too coarse to account for small targets such as pallidotomy

Fig 4. (A) Top row: axial MRI slices of our atlas volunteer. Bottom row: corresponding cryostatic photographs of Visible Female dataset. (B) Intermodality landmark-based deformation of volunteer's MRI to match Visible Female.

lesions (see later comments); (2) there is post-mortem degradation in the gray-white matter differentiation, which renders difficult an intensity-based deformation; and (3) the MR imaging and photographic datasets cannot be registered by simple rigid-body transformations.

DISCUSSION AND CONCLUSIONS

The difference vectors described previously compare favorably with both the pallidotomy lesion size (about 4 to 5 mm) and to the resolution of the MR scans (1-mm voxels); however, we note several improvable sources of error. The raw intensities of the pre- and postoperative images were different owing to autoscaling of the MR imaging scanner itself (this appears to account for the paradoxically greater error in the deformations of preoperative volumetric scans). There is postoperative shift of the brain within the skull owing to pneumocephaly. There was additive error in the postoperative subvolumes owing to the additional process of surface registration. Finally, the deformation algorithm itself was utilized in a low-dimensional form owing to run-time constraints. These issues, excepting the postoperative brain shift, are being successfully addressed in further research efforts—most notably an acceleration in the deformation algorithm that will enable higher-dimensional processing in shorter times, and that will significantly improve accuracy.¹¹

True intensity-based deformations between imaging modalities are not possible; to deform a photographic template to an MR imaging target, an MR image in register with the template is necessary as

an intermediate. In this way the deformation vector field from template to target MR image can be applied to deform the photographic dataset. Because the Visible Human MR imaging is inadequate for these purposes as described previously, we are pursuing two lines of research to create an in-register template MR image: (1) high-dimensional landmark deformations between MR imaging and photograph (Fig 4); and (2) de novo synthesis of an MR imaging dataset from a photographic dataset, using intensity/histogram mapping algorithms.¹²

We present a patient-specific deformable atlas that is easily integrated into our surgical navigation device. The atlas is a powerful new tool for the integration of information with the surgical act. This is the first time an outline atlas has been implemented to provide individualized, high-resolution data to the operating surgeon (see refs. 13 and 14). Our basic paradigm allows surgical navigation based upon photographic images, with a resultant great improvement in tissue contrast, and hence discernibility of small brain structures, over the best MR images. As such, this tool will allow preoperative and intraoperative guidance that is superior to any current system. It may, for example, improve preoperative selection of pallidotomy targets, thus eliminating the need for expensive and time-consuming intraoperative location procedures such as ventriculography. In addition, the introduction of the vast resources of neuroscience into the operating room via the WWW could revolutionize intraoperative decision-making and techniques.

REFERENCES

1. Pararas LG, Martin-Rodriguez JG: *Neurosurgery* 39:216-232, 1996
2. Smith KR, Frank KJ, Bucholz RD: *Comput Med Imag Graphics* 18:247-256.
3. Bucholz RD, Smith KR, Henderson JM, et al: *SPIE Proc* 1894:312-322, 1993
4. Maurer CR, Fitzpatrick JM: A review of medical image registration. In Maciunas RJ (ed): *Interactive Image-Guided Neurosurgery*. Chicago. AANS, 1993, pp 17-44
5. Joshi SC, Miller MI, Christensen GE, et al: *Vision Geometry IV* 2573:278-289, 1995
6. Christensen GE, Miller MI, Grenander U, Vannier M: *IEEE Computer* Jan 1996
7. The US National Library of Medicine, Bethesda, MD, 1996
8. Ricciardi TN, Owens JW, Department of Neurosurgery, University of Washington, Seattle, WA, 1996
9. Tindall GT, Cooper PT, Barrow DL (eds): *The Practice of Neurosurgery*. Baltimore, Williams & Wilkins, 1996, pp 3232-3233
10. Iacono RP, Shima F, Lonser RR, et al: *Neurosurgery* 36:1118-1127, 1993
11. Hammoud AM, Christensen GC, personal communication.
12. Mark KE, personal communication.
13. Greitz T, Bohm C, Holte S, Eriksson L: *J Comput Assist Tomogr* 15:26-38, 1991
14. Nowinski WL, Fang A, Nguyen BT, et al: *CVRMed '95*, Nice, France. Berlin, Springer-Verlag, 1995