METHODS **25,** 186–200 (2001)
doi:10.1006/meth.2001.1234, available online at http://www.idealibrary.com on IDEAL®

# Three-Dimensional Localization: From Image-Guided Surgery to Information-Guided Therapy

Richard D. Bucholz,[1] Kurt R. Smith,* Keith A. Laycock, and
Leslie L. McDurmont

*Bakewell Section of Image Guided Surgery, St. Louis University School of Medicine, St. Louis, Missouri; and*
**Surgical Navigation Technologies, Medtronic, Inc., Louisville, Colorado*

Image-guided surgery has become the standard of care for intracranial procedures. However, significant development is required before the benefits of this technology are brought to the majority of patients undergoing surgery. This article categorizes the areas wherein progress is needed, and indicates recent advances that may form the basis for the broad acceptance of this exciting technology. Emphasis is placed on a technique whereby preoperative imaging can be updated using low-resolution intraoperative imaging to reflect changes in anatomy caused by surgery, and on transforming image-guided surgery to information-guided therapy, in which diverse sources can be brought to bear at the time of greatest possible benefit, when the patient's anatomy is exposed for therapeutic intervention.

Image-guided surgery enhances intraoperative surgical visualization by coupling high-resolution three-dimensional (3D) scanning to the act of surgery. The potential benefits of image guidance are greatest for cranial surgery, in which visualization plays a key role in maximizing the utility of a surgical intervention while limiting the incidence and severity of postoperative complications due to inadvertent damage to normal tissue. For this reason, use of image guidance has become the standard of care for cranial interventions at many medical centers. This trend will grow as imaging techniques improve in resolution and diversify in terms of the information contained within the images. Scanning techniques currently exist that have the ability to demonstrate not only the anatomy, but also the function of the brain using noninvasive techniques. As imaging evolves to incorporate such additional forms of information, image-guided surgery will itself evolve into information-guided therapy as the power and ease of use of these new scanning systems become more readily available. This coupling of all pertinent information rather than just anatomical imaging is the true promise of computer-assisted surgery.

It is important to realize that information accrual is a truly interactive process, and one that can occur before, during, and after the therapeutic intervention. For instance, it would be ideal to include information from prior successful interventions in the determination of how to proceed on a given patient. An example would be making a lesion within the brain to relieve a neurological problem such as tremor. Currently, the surgeon selects an initial target based on prior experience and suggestions made by other experienced surgeons. The final lesion location is based on information obtained intraoperatively through the use of either recording or stimulation techniques. The final effectiveness of the procedure, which can be highly variable, is only known several months later after the patient has fully recovered. It is possible to selectively image the successful patients and determine precisely where in their brains the successful lesions are located. However, as patient brains differ in size, presence of atrophy, and functional organization, an improved initial target can be determined only by standardizing each successful lesion to a specific anatomical specimen, taking into account the variables already noted, and eliminating the anatomical variability between the successful patients. Once such standardization has been performed, the standardized atlas could then be deformed to match a patient's preoperative images, and the targeting process significantly improved for that particular patient.

This example demonstrates the extremely interactive nature of information-guided therapy, and indicates what

---

[1] To whom correspondence should be addressed.

1046-2023/01 $35.00

the requirements would be for a system designed to meet these needs. Rather than simply relying on structural information from computed tomography (CT) or magnetic resonance imaging (MRI), an information guidance system would have to be able to acquire information during and after surgery and organize that information using the 3D structure of the patient's brain. Further, the system would then have to be capable of fitting that information to a standardized atlas. This fitting process would entail nonlinear precise distortions of the three-dimensionally organized data to match the patient's data to an atlas, and the atlas to the patient. This form of distortion is termed elastic deformation, and becomes a key component of the system, along with the ability to use and acquire diverse three-dimensionally organized information, which hereafter will be called 3D datasets.

Finally, an information-guided therapy system must take into account the fact that the patient's anatomy can also become distorted during a surgical intervention. Such distortions can be induced by removal of tissue, drainage of fluid, or physiological changes within the patient's body. These distortions must be taken into account not only for any data acquisition occurring during surgery, but also to update the system's depiction of anatomy. Although the same scanning used preoperatively could be used intraoperatively, it is unlikely that imaging technology optimized for high-resolution depiction of anatomy could also be optimized for use when access to the patient's anatomy is paramount, as with a surgical procedure. It is therefore probable that, in the foreseeable future, high-quality imaging obtained prior to a procedure will need to be updated using imaging optimized for the surgical environment, which typically has less resolution, more noise, and different imaging characteristics. The same elastic deformation used for information standardization can be employed by a potential system to track tissues as they move during surgery, and to deform the high-quality preoperative scans to depict position.

Information guidance systems will therefore require three additional characteristics as compared with the traditional image-guided systems of today. First, they will have to be able to use, and acquire, information of diverse nature relevant to the intervention before, during, and after surgery. This can be thought of under the general term of surgical planning. Second, the system will have to be able to dynamically track the patient's anatomy during the intervention, which uses intraoperative imaging. Third, the system will have to be able to elastically deform 3D information datasets prior to, during, and after a given procedure to match information to patient, information to atlas, and atlas to patient. It is clear that such a system will require much greater computational power than is currently seen with image-guided systems, and will have to be closely integrated with a variety of potential sources of such 3D information.

To perform an information-guided intervention, these three capabilities will be required in addition to current standard surgical routine associated with the use of image guidance. These steps must be carefully developed to fully realize the promise of information guidance, with attention paid to minimizing the intrusiveness of each step in changing current surgical routine. Only in this way can this technique, which holds so much promise, become widely adopted and applied to the benefit of our patients. As the diversity of information potentially useful to a surgeon for planning is key to the utility of the technique, the current status of this field is reviewed first, followed by a discussion of intraoperative imaging techniques. Third, the common element of elastic deformation is discussed as it exists today. Finally, further developments of steps common to information and image guidance are discussed to indicate how improvements may allow generalized use of information guidance for all therapeutic interventions. The topics will therefore be: preoperative planning, intraoperative imaging, elastic deformation, preoperative imaging, image registration, intraoperative tracking, intraoperative visualization, intraoperative system control, and modified effectors.

Some of the potential options available to accomplish these elements are described in this article, and related research is briefly touched on. The intent is not to give a complete account of all possible solutions, but rather to show the overall framework of how image guidance could evolve into information guidance. Special attention is given to those subjects that have a maximal impact on accuracy of the procedure, such as registration. Less detail is provided on the variety of preoperative images that are currently employed by surgical navigation systems, as other articles in this issue cover this important topic. Throughout the article, the potential benefits of this exciting technology are stressed to emphasize how information guidance provides the infrastructure to develop entirely new procedures and maximize the quality of cranial surgery.

## PREOPERATIVE PLANNING AND VISUALIZATION

Although a planning process does not typically precede current image-guided procedures, it is probable that planning will become routine as new sources of information become available, if for no other reason than to manage the diversity and sources of information being applied. Although this could be perceived as a complex drawback, it is anticipated that review of such information will result in improvement in the quality of the resultant intervention. A pilot would not consider flying a plane between two points without reviewing first the proposed route and second the weather conditions prior to takeoff. Further, the pilot would organize the weather conditions three-dimensionally with respect to latitude, longitude, and altitude, and, if necessary, use this 3D dataset to change the proposed path. Along the way, information gathered from diverse sources is acquired, changing the 3D dataset, and the plan may have to be changed once again. Although this potentially iterative and complex process is time consuming, it is far preferable to flying over unknown territory in uncertain weather. Similarly, surgeons can employ three-dimensionally organized information to avoid critical functional tissue and maximize the likelihood of effectively reaching the target of their interventions. This process is necessarily one of exclusion as well as inclusion in the planning process; a complex intervention can be impeded by consideration of information irrelevant to the goal of the procedure.

Surgical planning has been limited previously by several technical constraints. First, the sheer size of typical image datasets made them unwieldy to transfer and manipulate by inexpensive computers. A usual CT-scan dataset, consisting of 50 images taken at 512 × 512 resolution, requires 40 megabytes of disk storage, far greater than what could be easily manipulated by the computers routinely available just a few years ago. With the exponential growth in computational power, and a similar decline in cost, this barrier to surgical planning has effectively been eliminated, and the process has become much more common.

Next, for information to be used, it must be transported from its source of origin to the therapist. As these datasets are large, they have previously been transported by “sneaker net,” that is, walking with the dataset stored on some form of medium readable to both the information source, usually a scanner, and the planning device. This process has now been greatly simplified by the advent of the Internet, which connects diverse sources of information, and massive improvements in the capacity of networks to transmit large amounts of data, termed bandwidth. Given the propagation of the Internet into every part of society, it is likely that almost every device used in the planning process will be connected over a high-bandwidth channel in the near future.

Third, a standardized fashion of collecting and organizing such large datasets is required to promote sharing over a diversity of devices. Such a standard has already been developed in the form of DICOM, a standard for radiology. This same standard could be easily enhanced to handle all forms of three-dimensionally organized information. DICOM is used by programs such as ePiphany (Medtronic, Broomfield, CO) to enable transmission of image data directly from scanners to a variety of inexpensive computers equipped with nothing more than a web browser and a high-speed connection to the Internet (see Fig. 1, a screen grab of an ePiphany screen). Such programs allow planning to occur anywhere there is a computer and Internet access, and will make planning far easier to implement routinely.

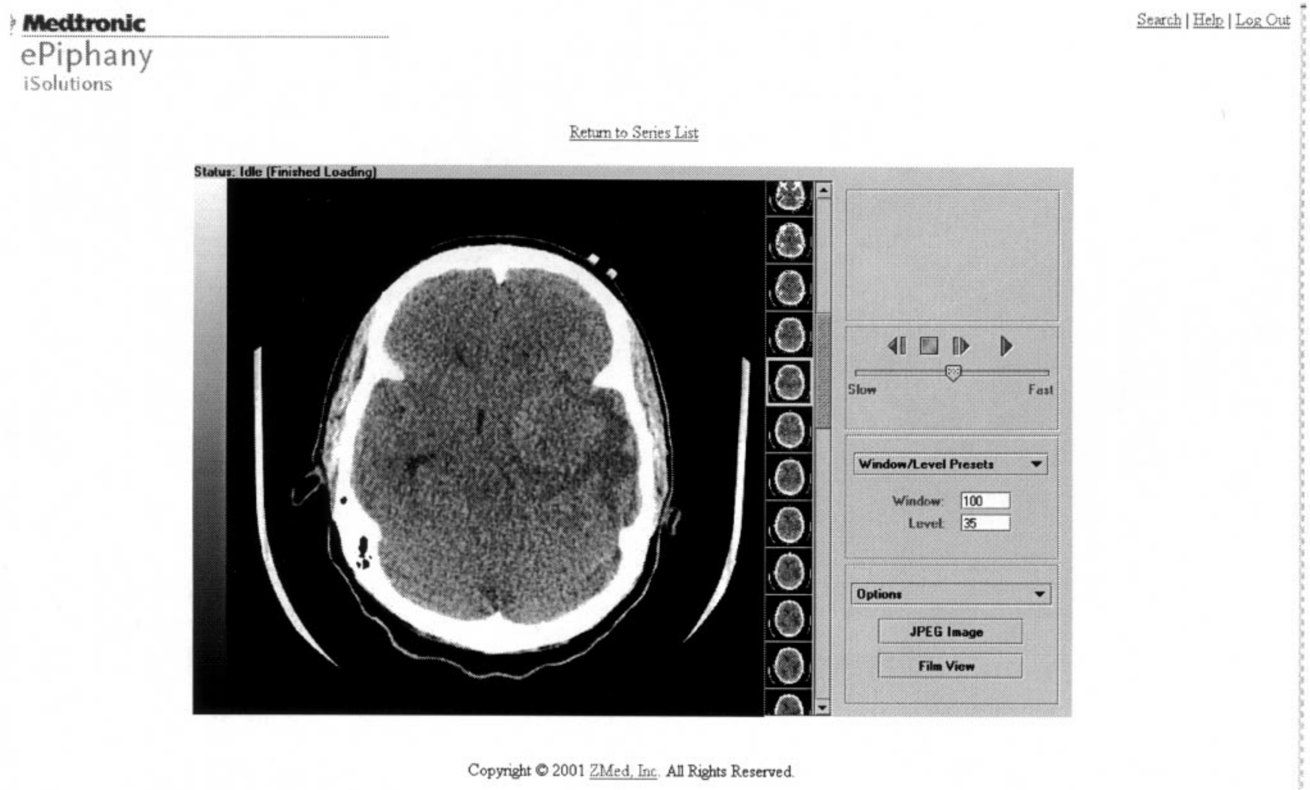
Finally, to make an effective plan, the therapist must use the preoperative images as a virtual object on which the proposed surgery can be practiced. Given that these images are three-dimensional in nature, and common computer displays are strictly two-dimensional in nature, the dataset must be presented in such a way that it can be viewed on a standard display. This process of altering the images to accommodate the limitations of current computers is termed rendering. As a standard rendering of this virtual object would show the surface of the patient, the full utility of the dataset cannot be realized unless the surgeon can peer into the dataset by rendering the surface of the patient either totally, or partially, transparent. This complex process of producing rendered 3D images and manipulating them to gain an appreciation of the structure of the dataset is termed visualization. Programs such as Analyze (Mayo Foundation, Rochester, MN) can produce these renderings easily on standard computers.

An alternative for 3D visualization on 2D video displays is to use hardware devices capable of rendering separate images to each eye of the therapist. Such stereoscopic displays consist of head-mounted devices and dual projection systems with synchronized projection. These specialized devices are currently expensive, but as other applications increase their demands for such visualization the price should decrease.

## INTRAOPERATIVE IMAGING

A critical limitation of image-guided systems is the fact that intraoperative position is displayed using images taken preoperatively. This is satisfactory for single rigid bodies such as bone, but for soft tissue any movement occurring between imaging and surgery results in an error much larger than that inherent in the components of the navigational system. Likewise, intraoperative shifts occurring as a result of tumor removal or fluid drainage can also result in navigational error. Several solutions have been suggested for this problem, including the intraoperative use of MRI and CT. Until recently, the size and fixed construction of imaging devices meant that intraoperative imaging could be performed only by physically transporting the patient from the operating room to the radiology department and back again, which was obviously impractical in many neurosurgical situations. Now, however, more compact and/or mobile imaging equipment has made it feasible to perform intraoperative imaging in the operating room itself.

There are now numerous reports of successful use of intraoperative MRI (3, 31, 40), with an MR scanner being installed in the neurosurgical operating room and integrated with a surgical navigation system to provide updated images as the operation progresses. Mobile CT units are also available that can be moved into the operating room as required (13). However, even with these improvements, it is highly unlikely that the quality and utility of the images produced by a device optimized for the operating room, where access to the patient is paramount, will ever match those produced in a radiology suite, in which image quality is paramount and access is of little concern. Given this reality, it is highly probable that imaging devices optimized for image quality will be used intermittently at best during a procedure, with the patient being moved in and out of the imaging device rather than being imaged continuously throughout the procedure. Relatively few imaging technologies are compatible with continuous use throughout a procedure. We have considerable experience with using an ultrasound device coupled to the navigational system (SonoNav, Medtronic Inc., Broomfield, CO) through the use of reflective spheres on the ultrasound probe, allowing precise comparison of the resulting ultrasound image with an MR image taken preoperatively and reformatted to match the orientation of the ultrasound image (see Fig. 2). The probe is



Status: Idle (Finished Loading)

Window: 100
Level: 35

Copyright © 2001 ZMed, Inc. All Rights Reserved.

**FIG. 1.** Typical screen shot of the ePiphany program produced by Medtronic showing a CT scan of a patient with a large left pterional meningioma. Any type of radiological image can be viewed on any workstation capable of running a web browser. Windows and levels can be dynamically set, pixels can be inverted, images can be shown side by side, and film loops can be made as the images are reviewed.

calibrated with respect to the spheres at the time of manufacture of the bracket holding the spheres to the probe. The system is then capable of rendering the preoperative image dataset precisely scaled and oriented to the ultrasound image. This allows the surgeon to note the sonic image pattern of specific structures around the target of the intervention and track these structures as they move. By sweeping the probe through an arc, an array of 2D images can be obtained, each with known orientation, and by placing these images together a 3D database composed of ultrasonic images can be created, thus fulfilling one of the requirements of an information guidance system.

Even with rapid improvement in ultrasonic imaging, it is clear that such a technique will not produce images with the tissue contrast and detail routinely available by MRI. Therefore, to satisfy the demand of the interventionalist to have image quality intraoperatively matching that available preoperatively, the ultrasonic dataset would be best used to track the movement of structures, reduce these movements to specific vectors within the reference system of the patient's anatomy, and then apply these vectors to their matched structures on the preoperative images. This concept would then produce a form of "pseudo-MRI" which could be used by the system to depict position with enhanced

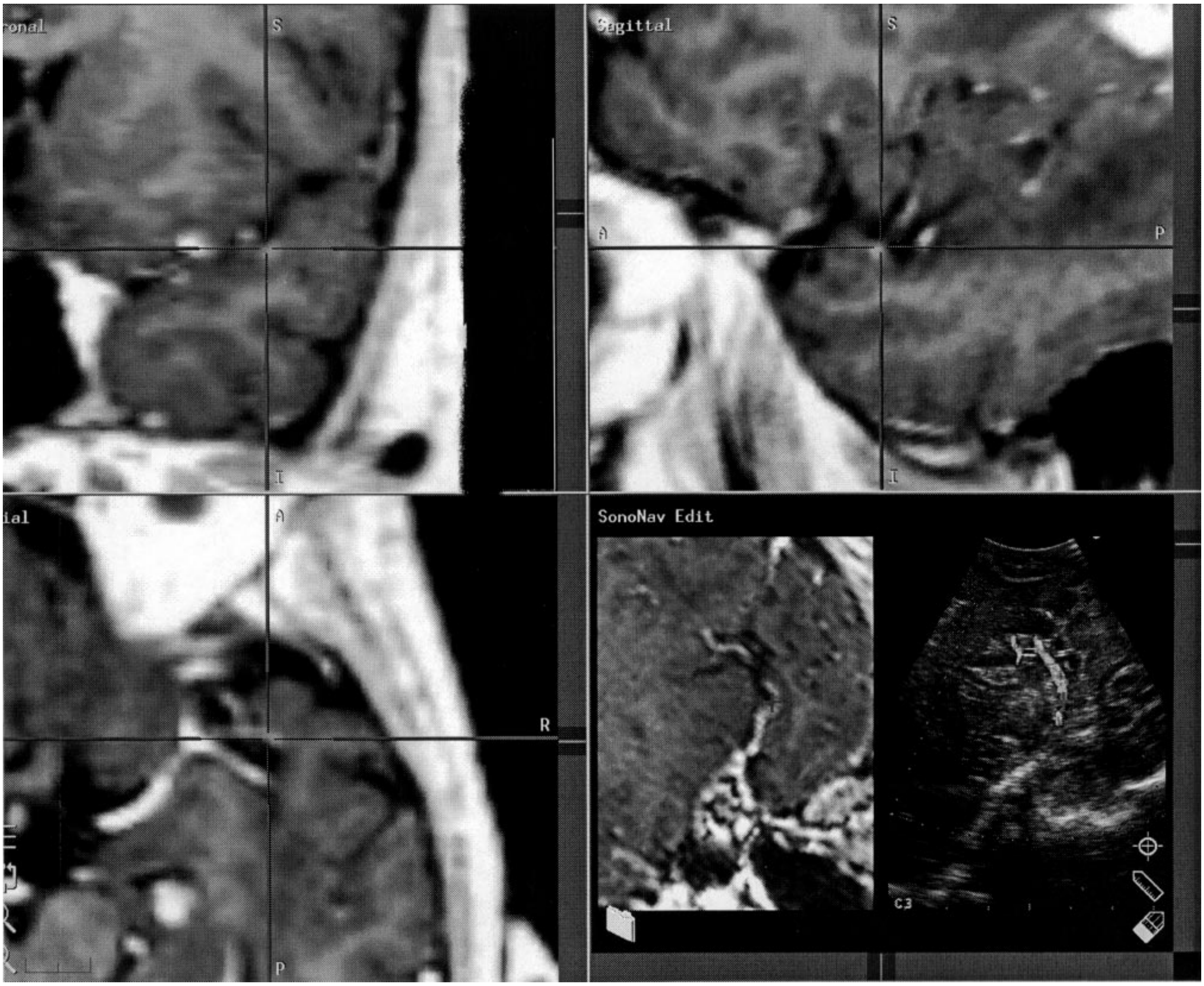


**FIG. 2.** Screen shot from a StealthStation connected to an ultrasound device with a probe being tracked by an optical digitizer. The bottom right-hand window shows the real-time ultrasound display being fed into the navigational system (right) matched to a computer-generated reformat of the preoperative MRI images (left). A marker (red cross) has been placed on an object of interest seen in the ultrasound view (the M2 segment of the middle cerebral artery). The location of this spot is indicated not only on the reformatted MRI image, but also on the standard orthogonal views as seen in the other three windows, with the crosshairs of these windows indicating the position of the object of interest in the ultrasound display.

accuracy. For an automated process to identify movable structures, the structures have to be easily seen and constant in the signal produced by their interaction with sound waves. An ideal candidate for such a structure is the vasculature of the brain, which has high contrast, when viewed with a Doppler ultrasound technique, against the background of the brain (Fig. 3). Tracking of vessels around a target would produce a vector field of deformation that could be employed by an elastic deformation technique to generate the necessary transformations of the preoperative dataset. Therefore, the same elastic deformation techniques employed to generate patient-specific atlases (see below) would be used intraoperatively to update the preoperative image dataset. Although such computationally intense manipulations are currently well beyond the power of most current image guidance systems, by the time such deformational algorithms have been clinically validated this computational power should be readily available either locally or through a network to a high-speed computational facility.

It should be clear that the specific intraoperative imaging technique to be employed is best determined by careful appraisal of the therapeutic plan and goals. Certain procedures may be easily performed within a high-resolution scanner and will not need deformational techniques. Other procedures will need functional updates, such as those obtained by intraoperative neurophysiological testing. The preoperative planning process will require contemplation and selection of the most appropriate intraoperative data acquisition process.

## ELASTIC DEFORMATION

While images of the patient's specific anatomy are obviously essential for navigational purposes, it would be highly useful to relate the patient's anatomy to atlases demonstrating the location of specific structures not detectable on current imaging techniques. For example, the location of the corticospinal tract cannot be detected on standard MRI imaging, and can be inferred only from comparison to other patients, usually in the forms of anatomical atlases. This need to have reference images available is especially great in situations where abnormal anatomy or suboptimal image quality is encountered. Printed brain atlases have, of course, been used in planning stereotactic procedures for decades (32, 36), but only in recent years have electronic brain atlases become available (27). The images in these atlases can be conformed to a patient's scans in two and three dimensions using nonlinear warping or deformation techniques (9, 28), thereby allowing limited interactive definition and labeling of stereotactic targets. Work is currently underway to integrate such a deformable brain atlas into the surgical navigation system, thereby enabling coregistration of the atlas images with the patient's preoperative scan information to be performed on the navigation system itself and subsequently displayed during the operation. At present, the fitting of atlas images to scan data is still a time-consuming process, but it is theoretically possible that future developments might enable updated images to be similarly matched intraoperatively (Fig. 4).

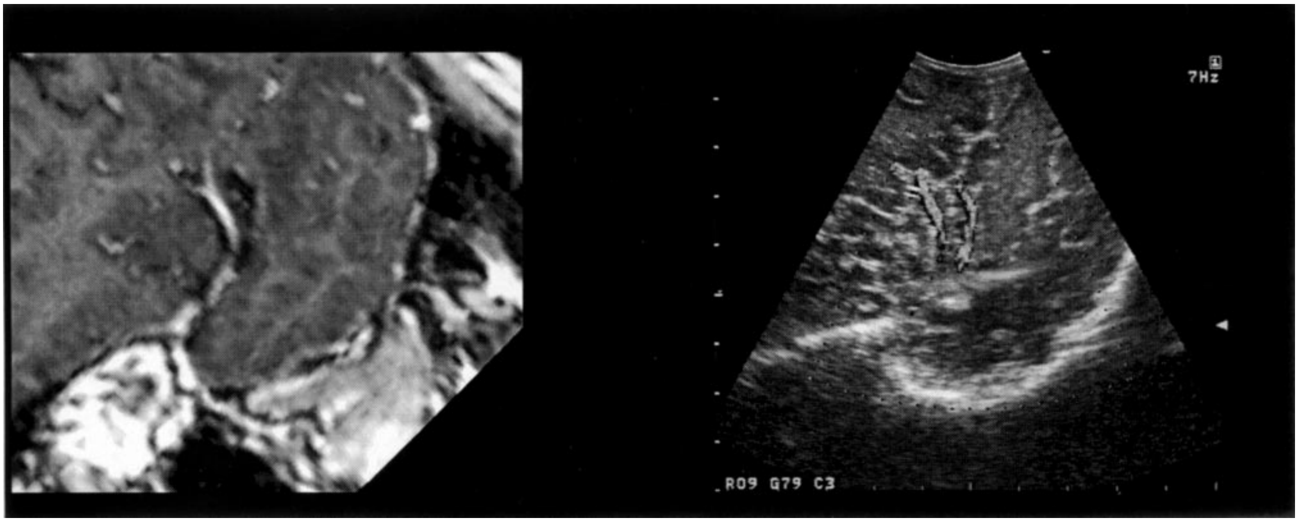


**FIG. 3.** Side-by-side intraoperative ultrasound view (right) and reformatted preoperative MRI (left). Note the vessels in the Doppler ultrasound view indicated in color. These vessels can be easily detected by the system and used to track the movement of the brain during a surgical intervention, and are also easily seen on the preoperative images.

One example of such an automated atlas is the work of Hogan *et al.* (16, 17) in performing an analysis of the hippocampus, a gray matter structure in the medial temporal lobe. Using a standard model of the hippocampus, and then deforming this model to match the anatomy of a patient's brain as seen on an MRI dataset, the hippocampus can be differentiated from the surrounding gray matter, a process termed segmentation. By isolating this important structure, comparisons can be made between the left and right sides of the brain, as well as to normal patients. The technique has been compared to humans performing the same process and has been found to be more reliable than manual techniques (17). The technique has already been employed by Csernansky *et al.* (8) to detect subtle changes in the shape of the hippocampus in patients with schizophrenia. With additional development, it should become possible to locate structure and function in most clinical situations, including the challenging situation of anatomy deformed by the presence of a mass lesion such as a brain tumor. Once these techniques are commonplace, it can be anticipated that many atlases of information will be written, based on experience or observations, and the therapist will have a choice as to which atlas should be used for a particular intervention.

## PREOPERATIVE IMAGING

The utility of image guidance is conditional on the accuracy and content of the images used. The less distorted, more detailed, and highly resolved these images are, the more useful they will be for coupling to the surgical intervention. The growing interest in image guidance can therefore largely be attributed to the tremendous improvements made recently in the imaging of the central nervous system.

There are two major categories of images employed in cranial image guidance. The first category, structural imaging, has been available for some time, and depicts the structural anatomy of the patient. The major modalities employed for cranial navigation are computed tomography (CT) and magnetic resonance imaging (MRI). These techniques are largely complementary, as CT scans are of high resolution (images are usually 512 × 512 pixels in resolution) and have little geometric distortion. MRI scans are of lower resolution (the most common being 256 × 256 pixels) and are occasionally geometrically distorted due to irregularities in the magnetic field of the scanner or the presence of ferromagnetic objects, such as dental fillings, in the patient (35). However, MRI is capable of resolving a variety of soft-tissue structures (such as gray and white matter) using an almost infinite variety of scan protocols. This capability, coupled with the availability of contrast agents that clearly define the margins of soft-tissue lesions, results in MRI being used for most cranial interventions with the exception of tumors located primarily within the skull.

The second broad category of scanning techniques detects the position of function within the brain, and currently comprises positron emission tomography (PET), single-photon emission computed tomography (SPECT), functional MRI (fMRI), and magnetoencephalography (MEG). Functional imaging can be further categorized according to whether imaging is directly detected (such as in MEG) or indirectly inferred (usually by the detection of alterations in cerebral blood flow). Whenever possible, techniques that directly detect the location of function are preferred, as their resolution and accuracy are superior to those of techniques that rely on broad changes within the cerebral metabolism. Unfortunately, the decision on what type of functional imaging to employ is predicated on the local availability of functional scanners and the limitations of the various techniques in determining specific types of function.

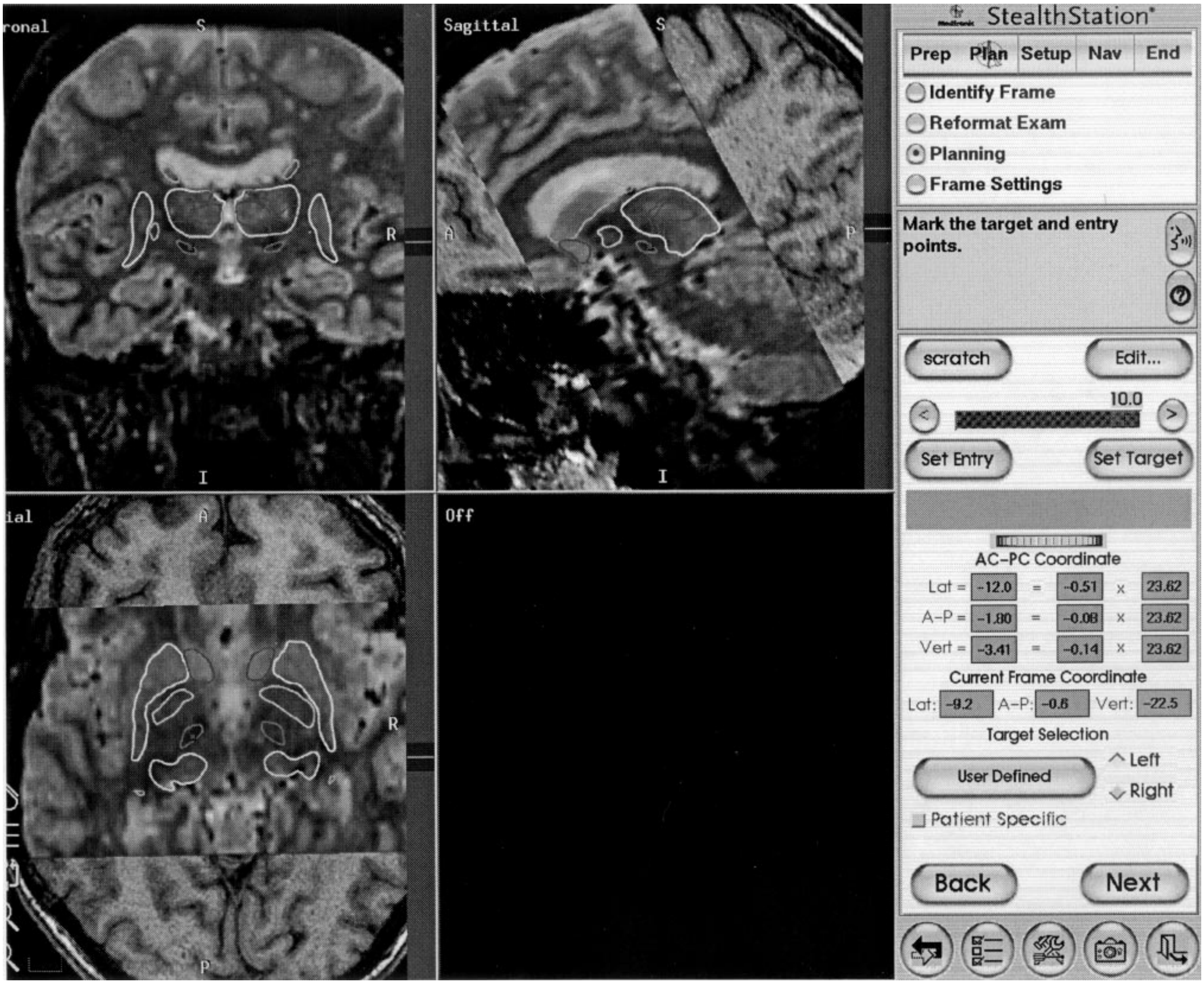
The usefulness of functional scans is derived not only from their ability to determine the position of normal function (thereby allowing the surgeon to avoid these areas), but also from the localization of abnormal function. An example of this utility is the use of SPECT in the evaluation of epilepsy intractable to medication. A radioactive tracer injected during a seizure will be absorbed by the brain in proportion to the amount of blood flowing through each part of the brain. This tracer has a high half-life that makes it possible to obtain a scan shortly after the seizure ends. The resultant SPECT scan will therefore provide an accurate picture of the blood flowing through each part of the brain during the seizure. Usually, the part of the brain responsible for generating the seizure will coincide with an area of high cerebral blood flow, and the image can then be employed to target the tissue to be removed in the hope of relieving the seizure activity.

An important consideration with the use of any of the current functional imaging techniques is the realization that the resolution of functional imaging is significantly coarser than that of structural imaging techniques, and is not capable of resolving a variety of different structures within the brain. Therefore, any use of functional imaging must be accompanied by the concomitant use of structural imaging to relate the function depicted to the patient's structural anatomy, and thus facilitate the process of image registration and preoperative planning. This coupling of one image to another is called image fusion, and can now be performed in a semiautomated fashion by a variety of commercially available programs. The resultant fused images provide detailed maps that allow surgeons to avoid critical functional tissue (previously termed eloquent cortex) while navigating to, and removing, abnormally functioning lesions. Fusions of SPECT, PET and MEG images with CT or MRI images are now routinely performed as a prelude to preoperative planning (21) (Fig. 5).

## IMAGE REGISTRATION

Preoperatively, 3D images are usually obtained in a fixed relationship to the anatomy of the patient's body. For example, CT scans consist of 2D images oriented in the anterior–posterior/medial–lateral dimensions, with subsequent images obtained either directly superior or inferior to the first image. By stacking the images one on top of the other, a 3D dataset is obtained that is oriented orthogonally to the patient's anatomical axes. This orientation can be described as a Cartesian coordinate system, with the *x* and *y* dimensions oriented anterior–posterior and medial–lateral respectively, and the *z* direction oriented in the superior–inferior dimension. The resultant images will also have a specific scaling, determined by the pixel size and number of pixels within the images, and a specific origin within the patient that is usually determined arbitrarily by the scanner software.

The approach to a specific target is rarely orthogonal



○ Identify Frame
○ Reformat Exam
● Planning
○ Frame Settings

Mark the target and entry points.

AC–PC Coordinate

Lat = -12.0 = -0.51 x 23.62
A–P = -1.80 = -0.08 x 23.62
Vert = -3.41 = -0.14 x 23.62

Current Frame Coordinate

Lat: -9.2 A–P: -0.6 Vert: -22.5

Target Selection

^ Left
⌄ Right

☐ Patient Specific

**FIG. 4.** Patient-specific atlas. StealthStation display showing two independent MRI datasets (T1-weighted and T2) coregistered to each other. Superimposed upon these gray scale images is a color atlas of the deep cerebral nuclei. The atlas from which the contours of these nuclei have been obtained has been elastically deformed to match the anatomy of the patient. Note the close correspondence between the atlas and the underlying structural anatomy. Image courtesy of Dr. Jaimie Henderson, Division of Neurosurgery, Saint Louis University School of Medicine.

to the anatomical axes of the patient. A surgeon will prepare an entry point on the patient (the surgical field) that minimizes distance to target, damage to critical functional tissue, and amount of retraction needed. The resultant surgical field can also be described as a second Cartesian coordinate system, with the *x* and *y* axes in the plane of the surgical field and the *z* axis perpendicular to this plane. To indicate a position within the surgical coordinate system using the preoperative images, a translational algorithm must relate the two coordinate systems involved. This algorithm must allow for translation of the two origins, rotation of the axes, and scaling of the axes as well. The technique by which this algorithm is performed is termed registration of the image dataset.

Previously, this relationship was determined using a device rigidly attached to the patient's head during imaging and subsequent surgery. The device, called a stereotactic frame, essentially solved the problem by making the coordinate systems identical. Examples of these devices include the Brown–Roberts–Wells (BRW) stereotactic frame (23) the Cosman–Roberts–Wells (CRW) frame, the Leksell G, and other frame-based stereotactic devices (7, 20, 26, 33). These were used primarily for tumor biopsy and for functional neurosurgery. However, frames are uncomfortable for the patient, restrict access by the surgeon to the surgical field, and are poorly suited to determining the position of hand-held surgical instruments on a continuous basis.

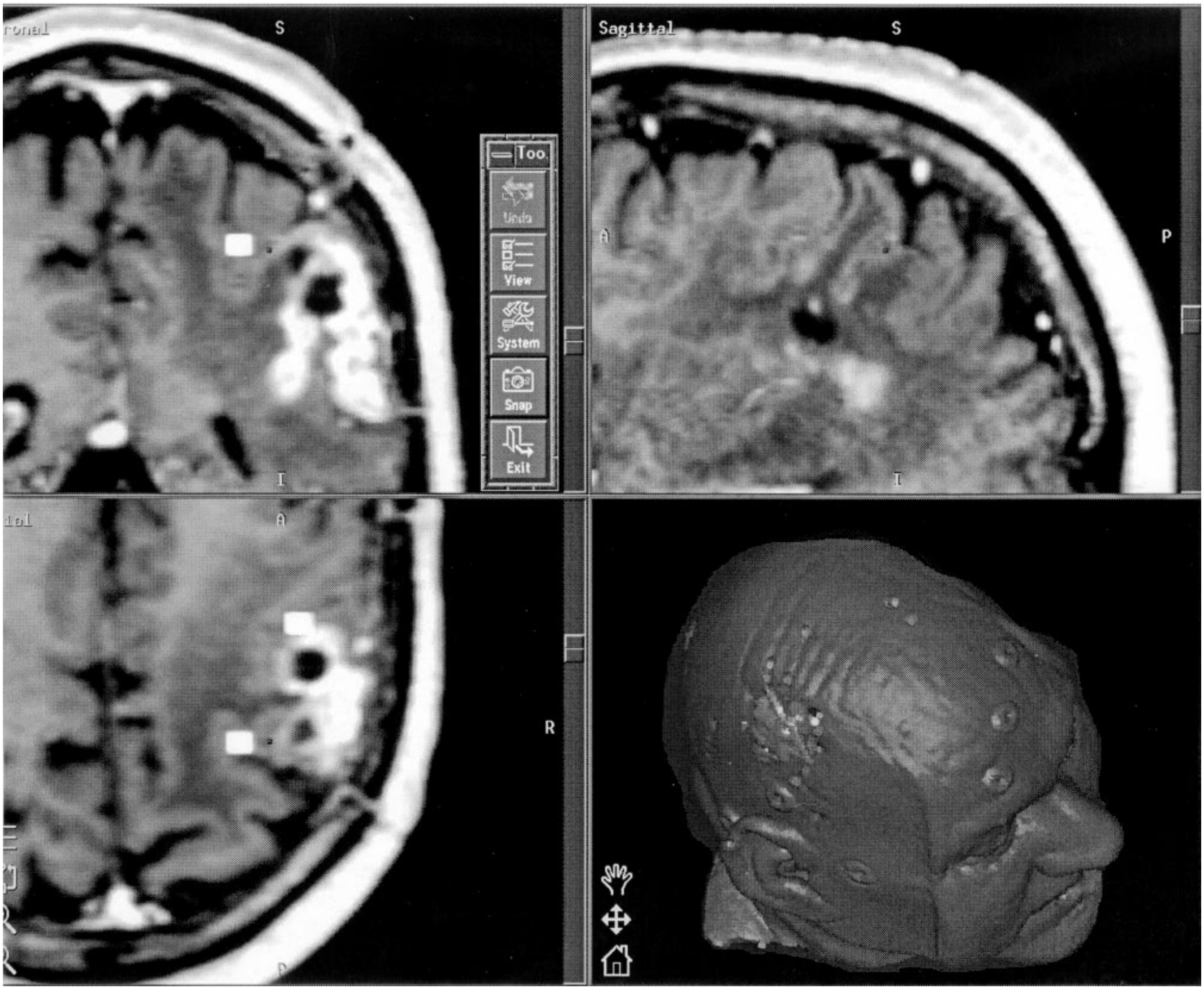


**FIG. 5.** MEG information fused on structural imaging. A StealthStation screenshot of a patient with a left anterior parietal intrinsic glioma. The patient has undergone mapping of the motor cortex using MEG indicated by small white squares on the orthogonal views and purple spheres on the 3D rendering. Note the proximity of the motor cortex to the area of abnormality indicated by contrast enhancement.

Planning must occur after data acquisition and immediately prior to surgery, a time constraint that may result in employment of suboptimal trajectories. Furthermore, frame-based systems are designed to confine the surgeon to a specific surgical plan rather than allowing unrestrained movement during the procedure (7). The use of a stereotactic frame for continuous localization is therefore both time-consuming and labor-intensive. Even though framed stereotactic registration solutions were generally computationally simple and accurate, their use effectively coupled the act of imaging to the act of surgery, and rendered image-guided procedures much more complicated to schedule and execute. More detailed mathematical analysis of the effect of localization devices and registration methods on the application accuracy of these different frame systems has been published elsewhere (43).

The use of stereotactic frames has now been largely obviated by improvements in the accuracy of diagnostic imaging and spacing between subsequent scans in the dataset (25, 30, 39), coupled with advances in registration techniques (15, 29, 41, 42). Frameless systems eliminate the discomfort and access problems of framed techniques, while providing real-time continuous indication of position (1, 12, 19, 22). These systems expand the use of stereotaxis to vascular, trauma, skull base, and spinal surgery. Rather than bolting a marker system to the head, most systems now use images obtained with markers, called fiducials, attached to the patient. By pointing to these markers using the surgical coordinate system, while indicating the position of the markers in the image coordinate system, an algorithm can be developed that relates the translation, scaling, and rotation of the surgical coordinate system to that used to obtain the images. Fiducials are now routinely employed in almost all surgical navigational systems. For most neurosurgical applications, adhesive fiducials attached to the patient's skin surface are quite satisfactory. Implanted fiducials directly attached to the skull may offer increased accuracy in certain situations (24, 38), notably when operating on the posterior fossa, but the invasive nature of the implantation procedure makes them undesirable for routine use.

For fiducials to be used during registration, they must be visible in both the operative field and the image data set. Currently, doughnut-shaped fiducials are employed that contain a material that is visible on both CT and MRI. These fiducials provide fixed reference points and are used to relate the two coordinate systems. Preoperatively, the fiducials are identified in the image data set. After the patient is positioned in the operating room, a registration probe is used to touch each of the scalp fiducials while the navigational system is told which marker is being touched. Four to ten fiducials can be used, with a greater number of fiducials usually yielding improved accuracy. The computer then calculates a set of transformations that relate the surgical coordinates to the corresponding image coordinates.

One drawback with fiducial-based registration is that the diagnostic imaging is usually performed without fiducials in place, necessitating a second round of imaging prior to surgery. This is not only expensive, but results in increased radiation exposure and discomfort for the patient. An alternative approach to registration is to use surface matching techniques. These techniques usually employ three or four anatomical landmarks to roughly align the images to the anatomy of the patient, and then, by taking points at random over a surface present on the patient, the contours can be matched to each other. As no fiducials are involved, it is possible to use the original diagnostic images in conjunction with the laser-generated contours, thus avoiding the need to reimage the patient. Although this technique works well for rigid contours such as the lamina during spinal surgery, physically touching the scalp during the contour acquisition process results in deformations of the skin, making this technique problematic and error-prone for cranial registration. A touch-free technique has therefore been developed, in which contour matching for cranial applications is performed using a handheld laser-based range-finding device (5). Points in the surface scan that do not reflect the shape of the patient (e.g., those arising from the reference arc or headholder) will contaminate the registration, so these must be removed. Software to automatically delete such contaminating points from the data has now been developed and demonstrated to be effective (4).

Studies continue to investigate the relative accuracy of fiducial markers versus facial landmark and surface matching techniques. Fiducials have generally been found to be more accurate than facial landmark-based methods (37), but the accuracy of surface contour matching continues to improve, and may surpass that of the fiducial method (4).

## INTRAOPERATIVE TRACKING

Most navigational systems consist of a device to track the operative movement of surgical instruments and the patient's body, and display the position using a computer workstation. The author was the inventor and co-developer of a popular system, the StealthStation (34), a surgical navigational device developed and marketed by Surgical Navigation Technologies, a division of Medtronic, Incorporated, of Louisville, Colorado. In the remainder of this paper, the StealthStation is used to demonstrate the functionality that should be present on any navigational device being considered for purchase by a neurosurgeon.

The StealthStation consists of: (1) a UNIX-based workstation which, by communicating with the other components of the system, displays position on a high-resolution monitor or head-mounted display; (2) an infrared optical digitizer with camera array; (3) a reference light-emitting diode (LED) array (e.g., a reference arc); and (4) surgical instruments modified by the addition of LEDs. Optional components of the system include a robotically controlled locatable surgical microscope and surgical endoscopes modified by the placement of LEDs.

### Optical Digitizer

The optical 3D digitizer uses infrared light either emitted by LEDs or reflected from spheres to locate and track instruments in surgical space. The LEDs or reflective spheres are attached to surgical instruments, microscopes, or endoscopes, as well as to a reference arc rigidly attached to the patient, and are detected and focused by charge coupled device (CCD) cameras which are mounted in a linear array and suspended over the surgical field in such a manner that all the spheres or LEDs are continuously visible to the array. Optical digitizers have been employed in almost all surgical navigational systems for some time, and have therefore matured considerably, becoming very accurate and robust.

The CCD cameras of the optical digitizer are arranged so that the field of view of each camera is perpendicular to the field of view of the other cameras. Within each camera, a lens focuses light onto a high-resolution CCD. As a surgical instrument equipped with either LEDs or spheres, or the reference arc attached to the patient, moves within the operational volume of the digitizer (for most systems, this is a cubic meter of space called the “sweet spot”, a unique element of each CCD is illuminated, providing positional information in the plane of the camera (or planes, for 2D CCD cameras). By triangulation, the position of the LED, and thus the surgical instrument, in 3D space can be determined. As the surgical instruments employed by the system have a geometry known to the system, and as the reference arcs are registered to the patient’s anatomy, both the position of the tip of the instrument and that of the patient can be determined by the system. By correlating the position of the instrument to the patient, the position of the instrument within the patient can be displayed.

### Alternative Digitizers

Although optical digitizers are widely employed, they suffer from the need to use either LEDs or reflective spheres that must be seen by the camera array. Therefore, the geometry between the tips of the instruments and the anatomy of the patient must be carefully defined and cannot change during the course of the procedure. This renders such digitizers useless for flexible endoscopy. For this application, new digitizers based on magnetic localization principles are being developed that can track a sensor deep within the body. However, the cost of these devices confines them to such specialized applications. Sonic digitizers have also been evaluated (6), in which the instruments are fitted with emitters that can be tracked by a microphone array.

## MODIFIED EFFECTORS

The term effector simply refers to those instruments used by a surgeon to produce a change in the anatomy of the patient, the said change being the point of the surgical intervention. Although surgical instruments constitute the largest part of this group of devices, it is important to realize that the more general term “effector” can be used to refer to anything used in the context of modern surgery. Hence, surgical microscopes, endoscopes, genetic material, drug polymers, and robots can all be classified as effectors that will soon be brought into the surgeon’s armamentarium. These new types of effectors, engineered for a specific effect, may soon displace the traditional instruments used by a surgeon, and provide the basis for the true utility of surgical navigation.

### Surgical Instruments

Essential components of a surgical navigation system are the instruments that, through modifications by the addition of LEDs or spheres, allow localization. The variety and number of such instruments define the functionality of the navigational device. The LEDs or spheres mounted on the surgical instruments must be visible to the camera array at all times. This precludes mounting an LED on the tip of the instrument, as the tip will not usually be visible to the cameras during surgery. The system therefore uses LEDs or spheres that are located at a given distance from the tip in the handle of the instrument. The length of each instrument and the distribution of LEDs are stored in the memory of the workstation, allowing the position of the tip to be easily calculated from the determined positions of the instrument’s LEDs. If the instrument can be depicted as being essentially linear, such as a forceps, then the minimum requirement for localization is two LEDs mounted in alignment with its tip. By adding a third LED for redundancy and by carefully integrating the placement of the LEDs into the design of the instrument, any surgical instrument with a linear geometry can be adapted for use as a localizing probe. Reflective spheres generally do not localize well if they are placed in a linear alignment, as reflective systems experience difficulty when the spheres partially occlude each other. For this reason, reflective arrays usually consist of at least three spheres in a nonlinear arrangement. This requirement, coupled with the size of such spheres, usually makes LEDs the detector of choice for microsurgical instrumentation.

A bayoneted instrument is commonly employed to allow surgery through a small opening. The offset design of a bayonet instrument allows the handle to be placed off the axis of the line of sight of the surgeon, and represents an ideal geometry for modification for the optical system. Since the bipolar coagulator is one of the most common bayoneted instruments used by a neurosurgeon, it is a logical choice for a localizing instrument. Additionally, a suction tube, dissecting probe, curette, drill guide, or ventriculostomy stylet can all be equipped with LEDs and localized.

If an instrument does not have a linear geometry, LEDs or spheres can be placed off-axis to allow complex 3D geometries to be effectively tracked. An example of such placement is the biopsy guide tube attachment used in the StealthStation system.

Although navigational systems are designed for freehand localization of surgical instruments, rigid fixation of instrumentation is preferred in certain circumstances to ensure that the instrumentation is aligned to a specific trajectory into the brain. Situations in which adherence to a surgical plan is necessary include tumor biopsy, insertion of depth electrodes for epilepsy, insertion of ventricular catheters, and functional surgery. For this purpose, a biopsy guide tube adaptor has been fabricated. The instrument attaches to the reference arc using a standard retractor arm with adjustable tension. The tube is equipped with four LEDs to provide redundancy.

The instrument is used by first selecting an appropriate target and entry point using the workstation software. The end of the guide tube is then placed at the entry point, and this positioning is verified using the system in continuous update mode. The most effective display for the workstation is the tri-oblique display, allowing the biopsy guide tube to be aligned with the surgical plan. The 3D view is useful for rough alignment of the biopsy tube, while the 2D views are used to fine-tune the projection of the guide tube down the surgical path. Once the surgeon has aligned the tube, it is fixed in the proper orientation, and the appropriate surgical instrument is inserted through the tube into the brain. The surgical plan generated by the workstation gives the depth to target from the entry point, and a depth stop is secured on the instrument at this distance. The instrument can then be inserted until the depth stop reaches the distal end of the biopsy guide tube. By using the appropriate reduction sleeves, radio frequency probes, catheters, biopsy instruments, and endoscopes can be inserted into the brain. In addition, biopsy needles, modified by the addition of an LED, have been fabricated so that the tips can be tracked continuously by the system as they are inserted into the brain (11).

### Reference Arc

It is not sufficient to determine the location of a surgical instrument in an arbitrary 3D coordinate system; the system must also be able to relate that location meaningfully both to the preoperative images and to the surgical field. The system must therefore track not only the surgical instruments but the surgical field as well. The system accomplishes this for cranial surgery by the rigid attachment of a reference arc equipped with five LEDs to the clamp securing the head of the patient. The reference arc defines the coordinate system of the surgical field.

Only three of the five LEDs on the reference arc must be visible to the camera array at any given time to establish a reference system in the operative field. The arc system is adjustable to any angle and can easily be positioned to remain out of the operative field. Registration is performed after the patient’s head is secured in the clamp but before the patient is prepped and draped. Once registration is accomplished, the reference arc is removed from the supporting arm to allow the patient to be draped in the usual manner; a sterile reference arc is then attached to the supporting arm using a threaded pin that penetrates the drape. This flexibility in positioning allows the navigation system to be used unobtrusively for any cranial procedure. By defining the surgical field, the reference arc also allows the camera array to be moved after registration to minimize line-of-sight problems. The reference arc also has a divot that serves as a calibration point for all of the instrumentation. Before using an instrument, the tip of the instrument is inserted into the divot and the digitizer activated. This allows the workstation to check the geometry of the instrument against the standard geometry stored within the computer. If there is any variance in the geometry, the instrument is rejected as having been deformed. The reference point also serves as a focal point for the microscope to allow calibration of the microscope to the surgeon's eyes.

### Localizing Microscope

Just as an LED-equipped surgical instrument can be tracked through space, an operating microscope can also be tracked relative to the surgical field and the position of the focal point displayed on the preoperative images.

One example of such a device that we have coupled to the StealthStation system is the Moeller "Smart Scope" (Moeller Microsurgical, Waldwick, NJ). This is linked to the surgical navigation system by attaching a bracket containing four LEDs to the back of the microscope. The system can then track the position of the microscope head relative to the surgical field. The microscope is equipped with a motor-driven variable focal length that is reported to the operative computer. By determining the position of the head of the microscope and adding the offset of the focal length, the position of the focal point of the microscope can be precisely calculated and displayed using the preoperative images. The crosshairs displayed by the computer system indicate the position of the focal point of the operating microscope. Note that with any microscope-based system the accuracy of the system deteriorates slightly as the focal depth of the microscope allows a range of tissue at varying depth to appear to be in focus.

This microscope can also be robotically controlled by the system. The microscope is equipped with motors that allow the head of the microscope to be rotated up and down and left and right. Using these motors, the workstation can drive the scope to focus on a specific point in the surgical field chosen by clicking on the spot as viewed on the workstation display. The system mouse is used to point to the position of interest, and then, by selecting the microscope drive function from the menu, the microscope is focused on that structure. Alternatively, the scope can be placed in the "follow-the-dog" mode, in which it automatically focuses on any point indicated within the surgical field by pointing with the modified surgical instrument.

### Image-Guided Endoscope

In neurosurgery, endoscopes are particularly useful for intraventricular procedures (2, 10, 14, 18), and a rigid straight fiberscope ("INCLUSIVE" endoscope, Sofamor Danek Inc, Memphis, TN) has been modified to work with the StealthStation. The endoscope is inserted into the brain through a modified sheath that is itself introduced into the brain over an obturator. Four LEDS are attached to the endoscope near the camera mount using a star-shaped adapter. The geometric configuration of the LEDs is programmed into the surgical navigational system along with the endoscopic dimensions.

The system also assists in entering the ventricle by allowing the stereotactic placement of the endoscopic sheath through a burr hole. The obturator and sheath are modified to fit over the registration probe of the system.

The LEDs mounted in line with the tip of the probe provide continuous positional information for the introducer tip during ventricular cannulation. After the sheath is placed into the frontal horn, the probe and obturator are removed and approximately 1–3 ml of cerebral spinal fluid (CSF) is drained to confirm intraventricular placement. Additional CSF drainage is replaced with warmed 0.9% saline delivered through the working channel of the endoscope to decrease the risk of ventricular collapse and subsequent subdural hemorrhage.

## INTRAOPERATIVE VISUALIZATION

The sole purpose of a surgical navigational system is to help the surgeon visualize the current location of surgical instruments within an operative field. Therefore, the manner in which this information is transmitted to the surgeon during the operation is paramount in determining the utility of the device. This function is performed by the surgical workstation, and is depicted on a growing variety of displays.

### Workstation

The StealthStation uses CT or MRI for intraoperative guidance. Images are obtained in the axial dimension (34), and the scanning parameters for each modality are adjusted to achieve roughly cubic voxels: For CT of the head, the field of view is 30 cm, scan thickness and spacing is 1 mm, and the number of images is adjusted to cover the entire cranial volume including the registration fiducials. No gantry tilt is used. For MRI of the head, 3D datasets of 124 images with a 256 × 256-pixel array are used, with a field of view of 30 cm and interscan spacing of 1.1 mm. This interslice spacing yields a dataset of cubic voxels with approximate dimensions of 1.17 × 1.17 × 1.3 mm. Image files are transmitted from the CT or MRI scanner to the surgical workstation over an Ethernet-based local area network, and are then converted to a standard file format. As an alternative backup in case of network failure, the files may also be transferred using the archival medium of the scanner, such as digital audio tape (DAT) or "write once, read many" optical disks (WORMs).

During surgery, three standard views (the original axial projection and reconstructed sagittal and coronal images) are displayed on a monitor at all times. A crosshair pointer superimposed on these images indicates the position of the surgical instrument, endoscope, or microscope focal point. A fourth window displays a surface-rendered 3D view with a portion cut away to show the current position of the LED-equipped instrument within the volume. An alternative view, the navigational view, produces images orthogonal to the surgical instrument rather than the patient, and is particularly useful for aligning the instrument with a surgical path.

As mentioned earlier, the image from the workstation is commonly viewed on a head-mounted display during the operation, thus eliminating the need for the surgeon to continually turn away to look at the monitor screen.

## INTRAOPERATIVE SYSTEM CONTROL

As navigational systems become more complex, the need for the surgeon to interact with the system during a procedure increases. This need will only intensify as new, more complex effectors, such as robots, are brought into the operating room. Furthermore, as these units proliferate into community hospitals, fiscal constraints will not permit an extra individual to be present for the sole purpose of making the unit function while the surgeon is scrubbed.

A variety of control techniques have now been developed that allow the surgeon to control the system while scrubbed. One technique involves the use of touch-sensitive flat panel displays that can be placed in a sterile bag and used for controlling the system as well as indicating position. Another solution is to incorporate voice recognition in the head-mounted display worn by the surgeon during a procedure. By placing a boom mike on these devices, voice recognition becomes possible.

## CONCLUSIONS

Stereotactic neurosurgery has evolved dramatically in recent years from the original rigid frame-based systems to current frameless image-guided systems that allow greater flexibility while maintaining superior accuracy. As these current systems continue to evolve, they are finding more applications, and image guidance has become a valuable tool in the treatment of a variety of neurological conditions resulting from infection, trauma, degeneration, or neoplasia.

The application of image-guided surgery is limited not by the pathology requiring treatment, but rather by the versatility of the stereotactic system being employed. If the system is simple, fast to use, and affordable, the benefits of its use will greatly outweigh any inconveniences, and relative indications for the use of image guidance will rapidly expand.

Image guidance will clearly never be indicated for cases involving global injury and very large lesions. Instead, it is most appropriately employed in cases involving relatively focal injury where accuracy and minimally invasive technique are important. However, as its limitations are overcome and it is coupled with other technologies (e.g., endoscopy), its versatility and areas of application appear to be almost limitless.

Current systems still contain several limiting characteristics that prevent expansion of their use to include pathology requiring immediate intervention. However, as registration technique further evolves to become simpler and faster, indications for image guidance will expand to encompass urgent cases, including acute trauma.

The future appears bright for the rapidly evolving field of image-guided neurosurgery. The medical marketplace, with its demands to improve cost efficacy, has served—and will continue to serve—as an incentive for identifying further applications to bring the benefits of minimally invasive surgery to the neurosurgical patient population.

## ACKNOWLEDGMENTS

The editorial assistance of Ms. Elizabeth Druhe in the production of an early version of this text is gratefully acknowledged.

## REFERENCES

1. Barnett, G. H., Kormos, D. W., Steiner, C. P., *et al.* (1993) *J. Neurosurg.* **78,** 510–514.
2. Bauer, B. L., and Hellwig, D. (1994) *Acta Neurochir. [Suppl]* **61,** 1–12.
3. Black, P. M., Moriarty, T., Alexander, E., Stieg, P., Woodard, E. J., Gleason, P. L., Martin, C. H., Kikinis, R., Schwartz, R. B., and Jolesz, F. A. (1997) *Neurosurgery* **41,** 831–845.
4. Bucholz, R., Macneil, W., Fewings, P., Ravindra, A., McDurmont, L., and Baumann, C. (2000) *in* Medicine Meets Virtual Reality 2000. (Westwood, J. D., Hoffman, H. M., Mogel, G. T., Robb, R. A., and Stredney, D., Eds.) IOS Press, Amsterdam.
5. Bucholz, R., Macneil, W. R., and Henderson, J. (1997) *in* Computer Assisted Radiology and Surgery: Proceedings of the 11th International Symposium and Exhibition (CAR'97), Berlin, June 1997 (Lemke, H. U., Vannier, M. W., and Inamura, K., Eds.), pp. 772–777, Elsevier, Amsterdam.

6. Bucholz, R. D., and Smith, K. R. (1993) *in* Interactive Image-Guided Neurosurgery (Maciunas, R. J., Ed.), pp. 179–200, AANS, 2 Park Ridge, IL.
7. Camacho, A., and Kelly, P. J. (1992) *Acta Nuerochir. Suppl.* **54,** 83–88.
8. Csernansky, J. G., Joshi, S., Wang, L., *et al.* (1998) *Proc. Natl. Acad. Sci. USA* **95,** 11406–11411.
9. Davatzikos, C. (1996) *J. Comput. Assisted Tomogr.* **20,** 656–665.
10. Drake, J. M. (1992) *in* Neuroendoscopy (Manwaring, K. H., and Crone, K. R., Eds.), pp. 103–107, Mary Ann Liebert, New York.
11. Germano, I. M., and Queenan, J. V. (1998) *Comput. Aided Surg.* **3,** 33–39.
12. Golfinos, J. G., Fitzpatrick, B. C., Smith, L. R., and Spetzler, R. F. (1995) *J. Neurosurg.* **83,** 197–205.
13. Grunert, P., Müuller-Forell, W., Darabi, K., Reisch, R., Busert, C., Hopf, N., and Perneczky, A. (1998) *Comput. Aided Surg.* **3,** 166–173.
14. Grunert, P., Perneczky, A., and Resch, K. (1994) *Minim. Invas. Neurosug.* **37,** 2–8.
15. Hardy, T. L., Koch, J., and Lassiter, A. (1983) *Appl. Neurophysiol.* **46,** 217–226.
16. Hogan, R. E., Bucholz, R. D., Choudhuri, I., Mark, K. E., Butler, C. S., and Joshi, S. (2000) *J. Digital Imaging* **13,** (2, Suppl. 1), 39–42.
17. Hogan, R. E., Mark, K. E., Wang, L., Joshi, S., Miller, M. I., and Bucholz, R. D. (2000) *Radiology* **216,** 291–297.
18. Jones, R. F., Kwok, B. C. T., Stening, W. A., and Vonau, M. (1994) *Minim. Invas. Neurosurg.* **37,** 28–36.
19. Kato, A., Yoshimine, T., Hayakawa, T., *et al.* (1991) *J. Neurosurg.* **74,** 845–849.
20. Kelly, P. J. (1991) *Acta Neurochir.* **52,** 26–29.
21. Kraus, G. E., Bernstein, T. W., Satter, M., Ezzeddine, B., Hwang, D.-R., and Mantil, J. (1995) *J. Image Guided Surg.* **1,** 300–307.
22. Kondziolka, D., and Lunsford, D. (1995) *Contemp. Nuerosurg.* **17**(8), 1–6.
23. Maciunas, R. J. (1995) *J. Image Guided Surg.* **1,** 208–216.
24. Maciunas, R. J., Fitzpatrick, J. M., Galloway, R. L., and Allen, G. S. (1993) *in* Interactive Image-Guided Surgery (Maciunas, R. J., Ed.), pp. 259–270. AANS, Park Ridge, IL.
25. Maciunas, R. J., Galloway, R. L., Jr., Fitzpatrick, J. M., *et al.* (1992) A universal system for interactive image-directed neurosurgery. *Stereotact. Funct. Neurosurg.* **58**(1–4), 108–113.
26. Morita, A., and Kelly, P. J. (1993) *Neurosurgery* **32,** 920–927.
27. Nowinski, W. L., Bryan, R. N., and Raghavan, R. (1997) The Electronic Clinical Brain Atlas: Multi-Planar Navigation of the Human Brain. Thieme, New York.
28. Nowinski, W. L., Fang, A., Nguyen, B. T., Raphel, J. K., Jagannathan, L., Raghavan, R., Bryan, R. N., and Miller, G. A. (1997) *Comput. Aided Surg.* **2,** 42–66.
29. Peters, T. M., Clark, J., Pike, B., *et al.* (1987) *Appl. Neurophysiol.* **50,** 33–38.
30. Reinhardt, H. F., and Zweifel, H. J. (1990) *Stereotact. Funct. Neurosurg.* **54/55,** 393–397.
31. Samset, E., and Hirschberg, H. (1999) *Comput. Aided Surg.* **4,** 200–207.
32. Schaltenbrand, G., and Wahren, W. (1977) Atlas for Stereotaxy of the Human Brain, Thieme, Stuttgart.
33. Sisti, M. B., Solomon, R. A., and Stein, B. M. (1991) *J. Neurosurg.* **75,** 40–44.
34. Smith, K. R., Frank, K. J., and Bucholz, R. D. (1994) *Comput. Med. Imaging Graphics* **18,** 247–256.
35. Sumanaweera, T. S., Adler, J. R., Napel, S., Glover, G. H. (1994) *Neurosurgery* **35,** 696–704.
36. Talairach, J., and Tournoux, P. (1988) Co-planar Stereotactic Atlas of the Human Brain. Thieme, New York.
37. Villalobos, H., and Germano, I. M. (1999) *Comput. Aided Surg.* **4,** 45–49.
38. Vrionis, F. D., Foley, K. T., Robertson, J. H., and Shea, J. J. (1997) *Neurosurgery* **40,** 755–764.
39. Watanabe, E., Watanabe, T., Manaka, S., *et al.* (1987) *Surg. Neurol.* **27,** 543–547.
40. Wirtz, C. R., Bonsanto, M. M., Knauth, M., Tronnier, V. M., Albert, F. K., Staubert, A., and Kunze, S. (1997) *Comput. Aided Surg.* **2,** 172–179.
41. Zinreich, S. J., Dekel, D., Leggett, B., *et al.* (1990) *Radiology* **177**(P), 217.
42. Zinreich, S. J., Tebo, S. A., Long, D. M., *et al.* (1993) *Radiology* **188,** 735–742.
43. Zylka, W., and Sabczynski, J. (1999) *Comput. Aided Surg.* **4,** 77–86.