6

The Magnetic System

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Image-guided neurosurgery has rapidly evolved in recent years, paralleling advances in computer technology and computerized imaging. Guidance depends on correlating an imaging data set with real space at the time of surgery. To accomplish this, surgical space needs to be defined with regard to a frame of reference. Traditionally, a stereotactic frame with rigid skull fixation has been used at the time of image acquisition to define space on the imaging data set as well as in real space at the time of surgery. Greater computer power and volumetric imaging have now made it possible to correlate volumetrically acquired images with surgical space by using surface landmarks on the patient's head, rather than frame placement, for imaging and surgery.[1] However, surface anatomical landmarks and skin markers do not have the same accuracy as a frame with skull fixation.

■ Frameless Image-Guided Surgery

In the absence of a frame, surgical space must be defined by rigid fixation of the head to the operating table at the time of surgery using a head holder. Subsequent surface registration of patient landmarks requires a probe that can be tracked within the defined space. A variety of methods have been employed to track probes in space. Some systems use a probe on a digitized articulated arm attached to the head holder.[2–3] Others use ultrasonic emission and triangulation.[4–6] Many systems use optical tracking and triangulation of a probe that is active (light emitting diodes)[7] or passive (reflective markers).[8] This requires an array of markers rigidly attached to the head holder that function as a frame of reference.

An alternative is to define space within a magnetic field by attaching a magnetic field generator to the head holder and then tracking a probe with an attached magnetic receiver.[9–10] This is the principle of the Cygnus-PFS system (Compass International, Rochester, MN) described in this chapter.

■ Magnetic Field Referencing of Stereotactic Space

A static magnetic field is used as a frame of reference once the patient's head is immobilized in three-point fixation. The magnet is attached to the head holder and remains immobile from the time of registration onward. When the patient is draped, the magnet remains concealed under the drapes. The receiver and probe are exchanged for an alternate sterile receiver and probe. Defining space with a magnetic field allows excellent continuous tracking of a probe during surgery because there is no interference with probe tracking such as that experienced with optical tracking systems where a line of sight must be maintained between the tracking cameras, reference markers, and probe markers. In theory, interference from metal objects within the surgical field may compromise tracking accuracy. In practice, this has not been an issue (see discussion of accuracy later in this chapter).

Applications and setup

Because stereotactic space is defined in relation to a magnet, the Cygnus-PFS system allows unprecedented

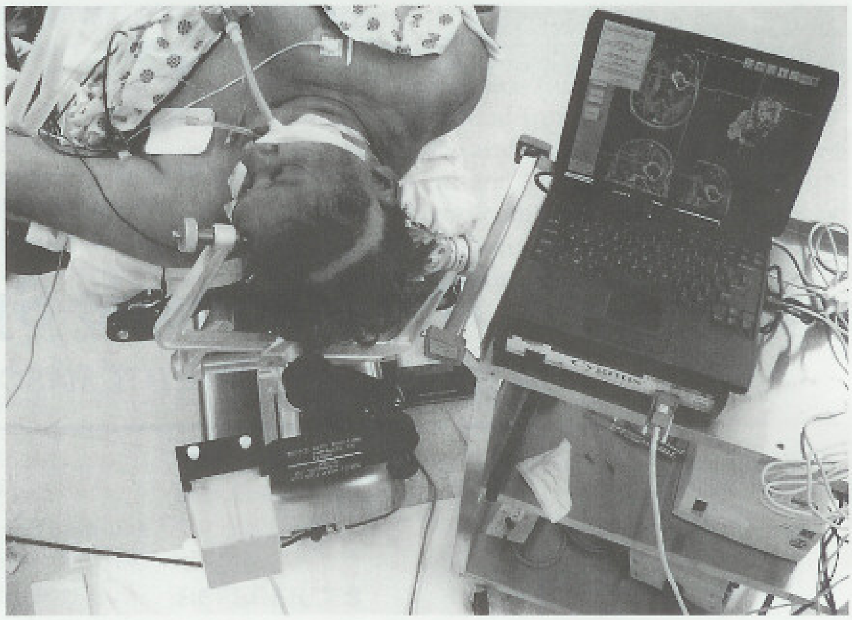

FIGURE 6–1. Cygnus-PFS setup for surgery illustrating magnet attached to head holder via L-shaped bracket, laptop computer, and magnetic control unit under computer (Compass International, Rochester, MN).

portability—neither tracking cameras nor cumbersome articulated arm systems are required. The core of the Cygnus-PFS system is the magnet with a control unit and a laptop computer (Fig. 6–1).[9] This allows for easy transport between hospitals. The magnet attaches to the outer starburst of a three-point head holder via an adjustable L-bracket. An optional stand with a touchscreen control panel/monitor is available for more sedentary use (Fig. 6–2).

Data acquisition is very efficient and requires less than 5 minutes. This is accomplished via an ethernet card or using an outboard digital archive tape (DAT) drive connected to the small computer system interface (SCSI) port of the laptop. The computer then builds three-dimensional models of the head for registration of landmarks in image space. A second data set can then be correlated to the primary data set, [i.e., computed tomography (CT) with magnetic resonance imaging (MRI)] thus allowing simultaneous use of two data sets during surgery (Fig. 6–3). Under "Image Registration," landmarks and fiducials are selected on the imaging data set for subsequent correlation with the homologous landmarks in real space on the patient at the time of surgery. This process of image and subsequent patient registration is similar in all commonly used image-guidance systems. The Cygnus-PFS laptop allows all the preoperative planning to be performed anywhere.

At the time of surgery, after the patient is positioned and in three-point fixation, the Cygnus-PFS magnet is attached to the head holder via an L-bracket. The laptop is connected to the electromagnetic control unit and the appropriate patient study is loaded. A nonsterile magnetic field receiver and probe are attached to the Cygnus control unit, and patient landmarks are registered on the patient by touching these with the probe. Following registration and draping, the receiver and probe are exchanged for a sterile receiver and probe and the system is ready for intraoperative use.

Features

The Cygnus-PFS has many of the same features as other image-guidance systems, including target volume planning, trajectory planning, and image correlation (image fusion). Image correlation can be used to correlate CT with MRI (see Fig. 6–3), different MRI sequences [i.e., spoiled gradient echo (SPGR) with fluid attenuated inversion recovery (FLAIR)], or functional imaging. Preoperative planning and image correlation with the Cygnus-PFS are particularly user-friendly and usually take less than 5 minutes.

Unique hardware features include not only a biopsy needle holder, but different-length probes that can be angled or straight and also used as suction probes. This is particularly useful during surgery because suction is the most commonly held tool during surgery. In this manner, image guidance can continuously demonstrate the position of the suction tip without the need to pick up a dedicated probe. We find this more practical than tracking bipolar cautery or any number of other surgical instruments. The Cygnus-PFS probes, including the suction probes, are all disposable, which is also a unique feature of increasing importance in contemporary practice.

The Cygnus-PFS has a number of extremely intelligent, useful, and instructive software features. Upon completion of patient registration at surgery, a registra-

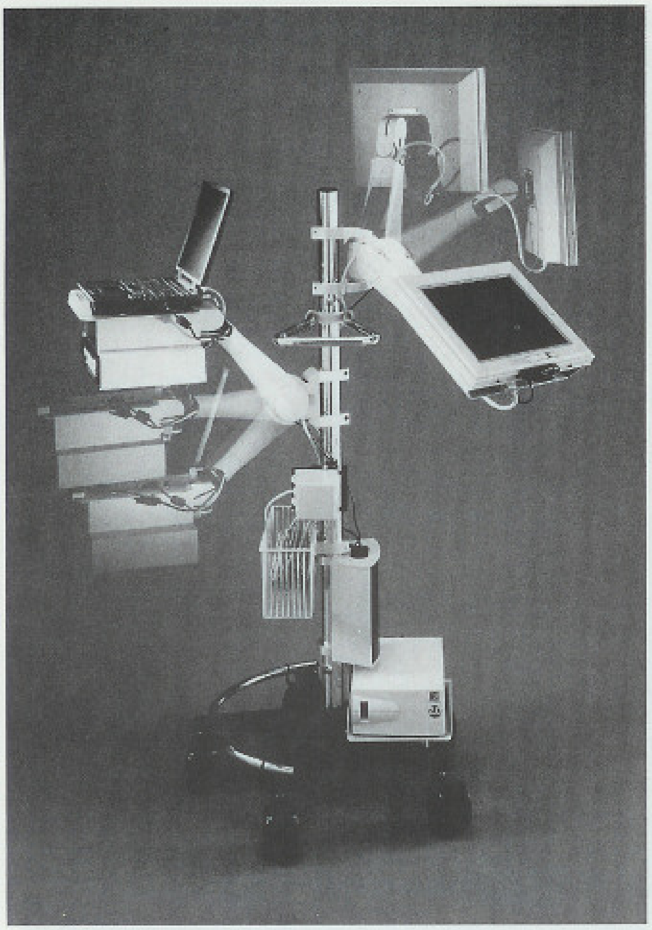

FIGURE 6–2. Optional Cygnus-PFS stand featuring movable touch-screen monitor (Compass International, Rochester, MN).

tion screen gives a calculated global accuracy (root mean square error), as do all image-guidance systems. In addition, a readout of the individual calculated error for each correlation point is given (Fig. 6–4). This is not readily available with many systems. Of particular interest, a feature called Show Registration on Images displays side-by-side images of landmarks in "image space" versus "real space" (Fig. 6–5). This feature has proven very instructive for understanding the source of inaccuracies at the time of patient registration, leading to higher true surgical accuracy.

During surgery there are a number of useful options. In addition to three orthogonal views (axial, coronal, and sagittal) a fourth "trajectory view" is available for simultaneous viewing (Fig. 6–6). Unlike trajectory views of some other systems, the orientation of the trajectory and the target can be altered by simply rotating the probe and receiver until a more anatomically and surgically intuitive picture is obtained. This obviates the need for multiple trajectory views. There is a simple one-step magnification feature that provides ideal enlargement of images (2× magnification) for smaller lesions. A single icon click switches between the primary imaging set and a second, correlated data set if this has been preplanned.

Lessons Regarding Accuracy in Image Guidance

Calculated accuracy

The relationship between image space and real space is basically a topological one, where each point in one needs to correspond to a point in the other. By selecting a finite number of points in image space and correlating these with equivalent points in real space, the image-guidance system finds an algorithm of the best match between the two sets. If a point moves (e.g., a skin marker near a head-holder pin site), the algorithm for the overall best match may or may not identify the true worst point. This is very well illustrated when performing a patient registration with the Cygnus. At any time, re-registering a point or eliminating a point will change the calculated accuracy values of all the other points because the algorithm tries to find the best match for the entire cohort of points and not points one at a time (see Fig. 6–4). We have found that having this information clearly presented leads to a better understanding of image guidance and does not really complicate the registration process. As expected, calculated accuracy is higher when using skull-implanted screw fiducial markers (Leibinger, Freiburg, Germany) than with adhesive skin markers or anatomical landmarks. The goal with most image-guidance systems is to obtain a calculated accuracy of less than 3 mm. Calculated accuracy usually improves to 1 mm or less when implanted skull fiducials are placed. Cygnus calculated accuracy on registration with implanted screw fiducials was 1.0 mm ± 0.4 mm (n = 33) as opposed to 2.0 mm ± 0.5 mm (n = 56) for skin markers.

True accuracy

It must be kept in mind that calculated accuracy does not represent true surgical accuracy, which depends on a number of factors. Stereotaxis with a frame and using CT imaging, which does not have the field distortions of MRI, can attain 1.0 mm accuracy at best.[11,12] All information regarding calculated accuracy must be compared with true surgical accuracy, preferably by verification of intraoperative anatomical landmarks. Visual verification of true accuracy should be obtained by selecting clearly recognizable anatomical landmarks during surgery. In Figure 6–6, the probe is placed so that it is almost touching the dome of an anterior communicating artery aneurysm seen on the images. This is an illustration of good true surgical accuracy.

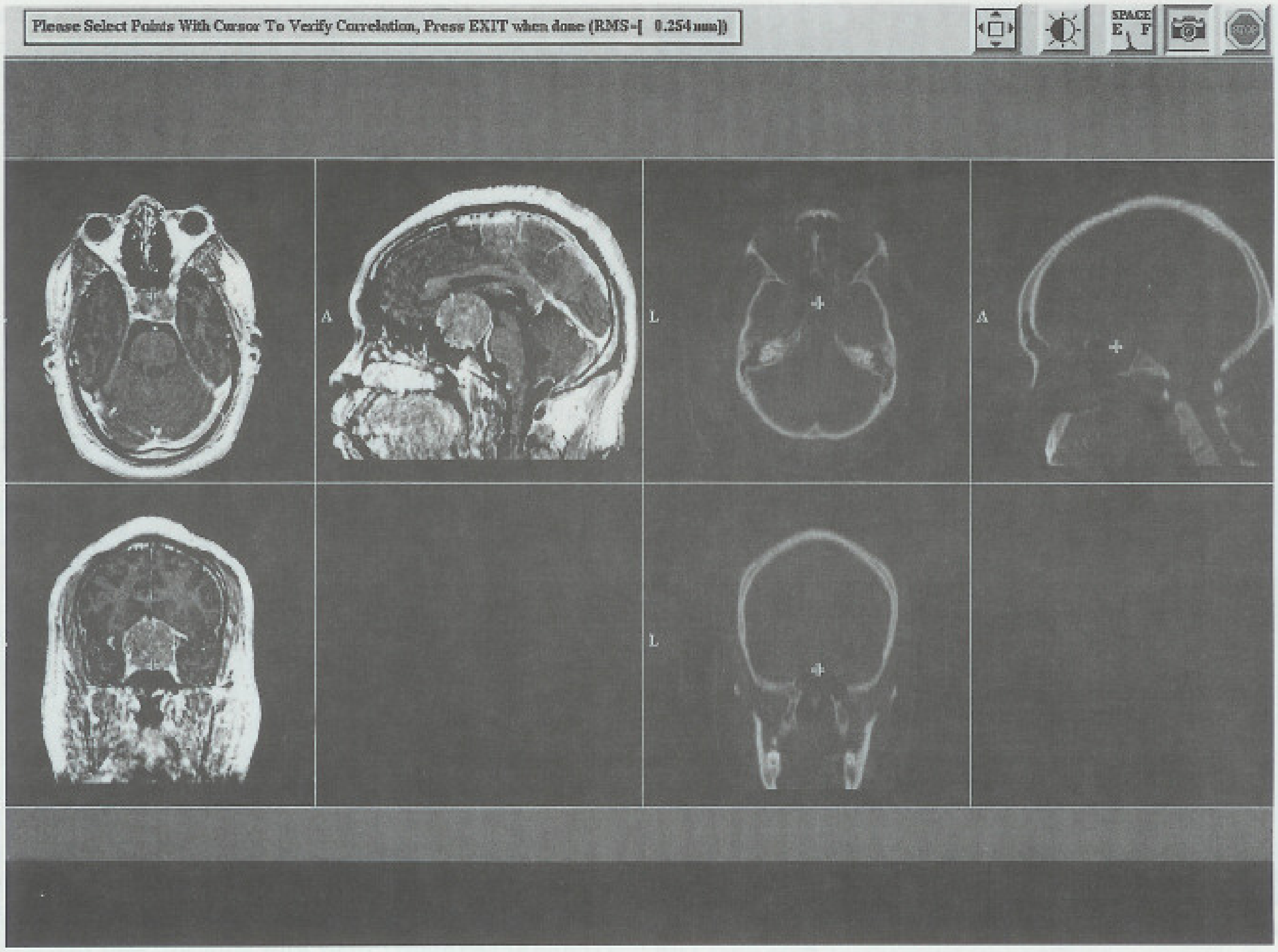

FIGURE 6–3. Image correlation of magnetic resonance imaging with computed tomographic data set.

Comparison magnetic/optic systems

Over the past 2 years we have conducted a study comparing the accuracy of a magnetic system (the Cygnus-PFS) with that of an optical tracking system (the StealthStation, Medtronic Surgical Navigation Technologies, Louisville, CO). Using a customized bracket, both systems were attached to the surgical head holder simultaneously in over 50 patients. Calculated accuracy at registration and true surgical accuracy were assessed and will be the subject of a detailed report elsewhere. For this chapter, the issue of true surgical accuracy is of the greatest interest. In the first 50 patients of the study, excellent true surgical accuracy was noted in 42 cases. Accuracy was poor with magnetic, but not with optical, tracking in three cases. Conversely, poor accuracy was noted with optical, but not with magnetic, tracking in three other cases. Both magnetic and optical systems had poor accuracy in the other two cases. Reasons for lack of surgical accuracy were unclear except in the two cases where inaccuracy was found using both systems. In these cases, poor accuracy was explained by the prone position, as discussed later in this chapter. With regard to the possibility of inaccuracies introduced into the magnetic field by metallic objects during surgery, we did not find this to be a problem. The introduction of a Budde Halo retractor system (OMI, Cincinnati, OH) during surgery did not seem to adversely affect the Cygnus-PFS. We did see some interference with the magnetic field when several large, self-retaining retractors were placed within an incision. This was easily corrected by removing all but one retractor, or by replacing retractors by traction sutures.

Overall, magnetic tracking and optical tracking appear to be comparable in terms of surgical accuracy.

■ Applications

The Cygnus-PFS has a number of practical applications in cranial surgery and can well be used by neurosur-

A

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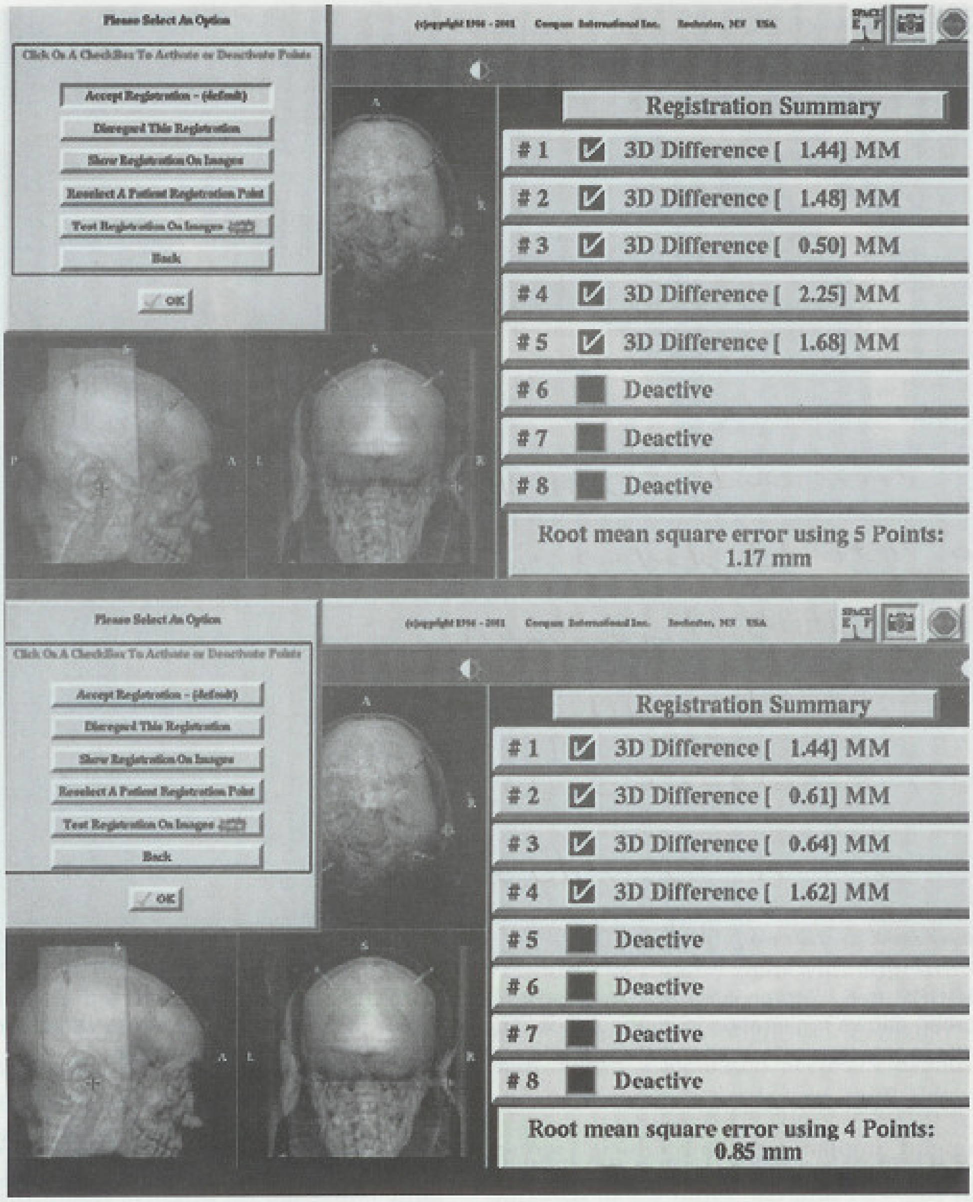

FIGURE 6–4. Registration readout screen using five points (A). Modified registration of the same patient after deactivating one point (B). The high calculated accuracy is a reflection of the use of implanted skull fiducials.

geons, ophthalmological surgeons, and ear, nose, and throat surgeons.

■ Neurosurgery

Tumors

The most obvious and common application of frameless stereotaxis in cranial surgery is for brain tumors. Regardless of the system that is employed, the principles and applications are similar. Preoperative planning can help determine the best surgical approach prior to surgery. In the operating theater, following registration, frameless stereotaxis can help center the incision and bone flap. Dural opening can be image guided as well as the approach and trajectory to deep-seated lesions.

Supratentorial

For small lesions, the advantages of image guidance for localization are obvious. This is particularly evident for small metastatic tumors, which are often not visible on the cortical surface. Because there is no frame, performing multiple small craniotomies for multiple metastatic lesions becomes more feasible. For particularly small lesions, deep locations, or posterior head regions, we would

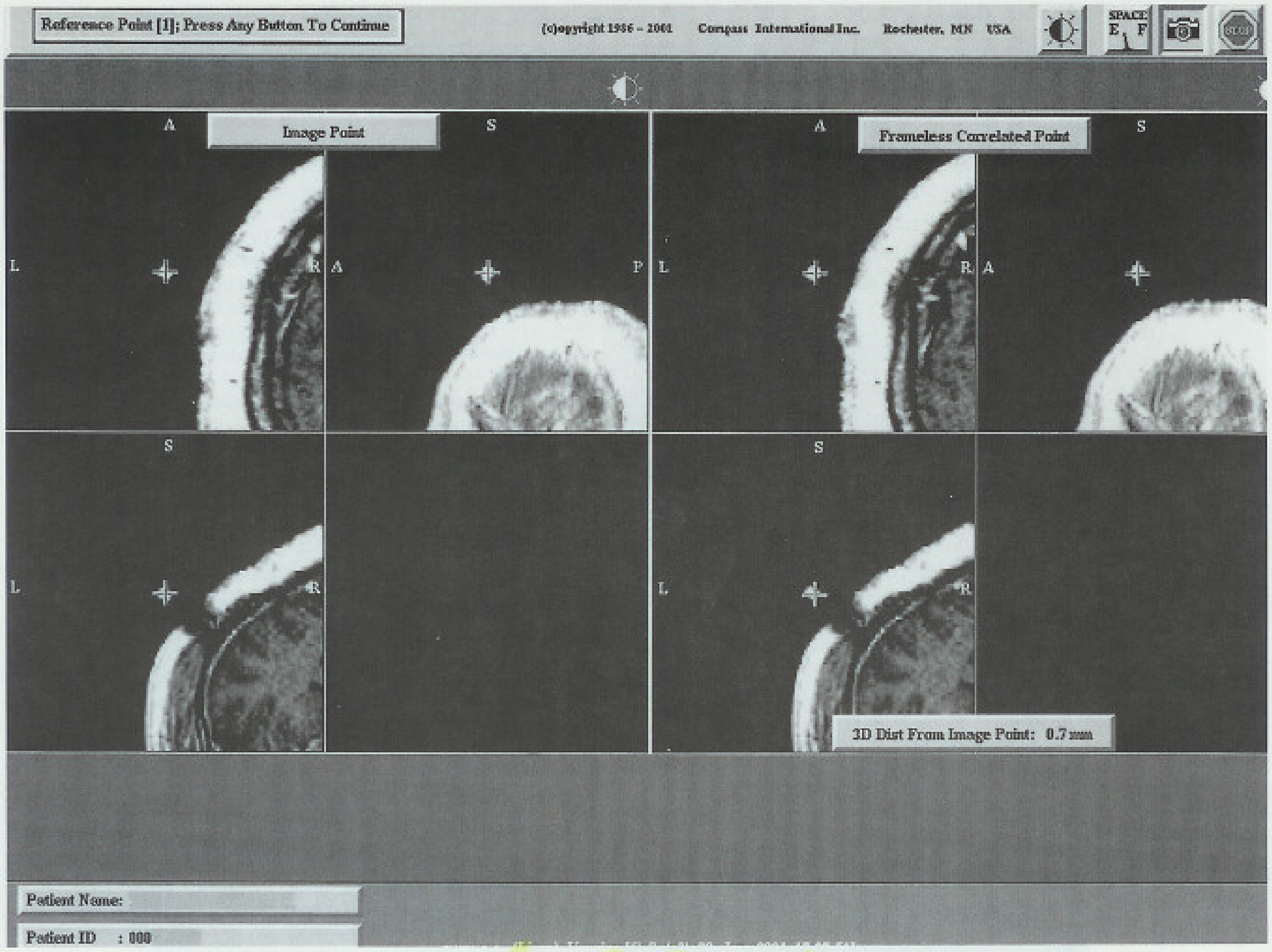

FIGURE 6–5. Screen shot of "Display Registration on Images" feature. The left side of the screen shows registration in image space. The right side of the screen graphically estimates the error in real space of each registration point and displays a corresponding image.

strongly recommend implanting skull fiducial screws, which, in our hands, results in framelike precision.

To preserve accurate image guidance, we usually try to keep tumor intact for as long as possible. In large tumors of softer consistency, this may not be possible. In these cases, internal decompression of tumor, while replacing the resected mass with cotton balls (our preference being Merocel surgical patties, Xomed Surgical Products, Jacksonville, FL) retains a reasonable degree of stereotactic accuracy. It is in this situation that the Cygnus-PFS suction probes have a particular advantage, giving constant imaging feedback. This can be illustrated with a recent case of a recurrent temporal lobe glioma where the deep aspects of the enhancing tumor were causing considerable shift of the midbrain and basal ganglia. Although we normally see no particular advantage to speed at surgery, the patient in question had an onset of pronounced electrocardiogram changes noted by the anesthesiologist shortly after dural opening. Urgent closure was discussed in view of a possible myocardial infarct. Prior to closure, a 5-minute temporal lobectomy and tumor debulking were performed with bipolar cautery and image-guided suction. Without changing instruments, we were able to ascertain depth of resection of the tumor in an essentially emergent situation. Postoperative imaging confirmed a 95% resection of enhancing tumor volume, which matched our intraoperative impression. Using another image-guidance system under similar time constraints would not have been realistic.

Infratentorial

We initially had very poor surgical accuracy in posterior fossa approaches, both with magnetic and with optical tracking systems, despite good calculated accuracies. Further study demonstrated a significant displacement of skin markers, which are imaged with the patient supine. With a prone or three-quarter prone surgical position, we were unable to obtain acceptable surgical accuracy until we resorted to systematic implantation

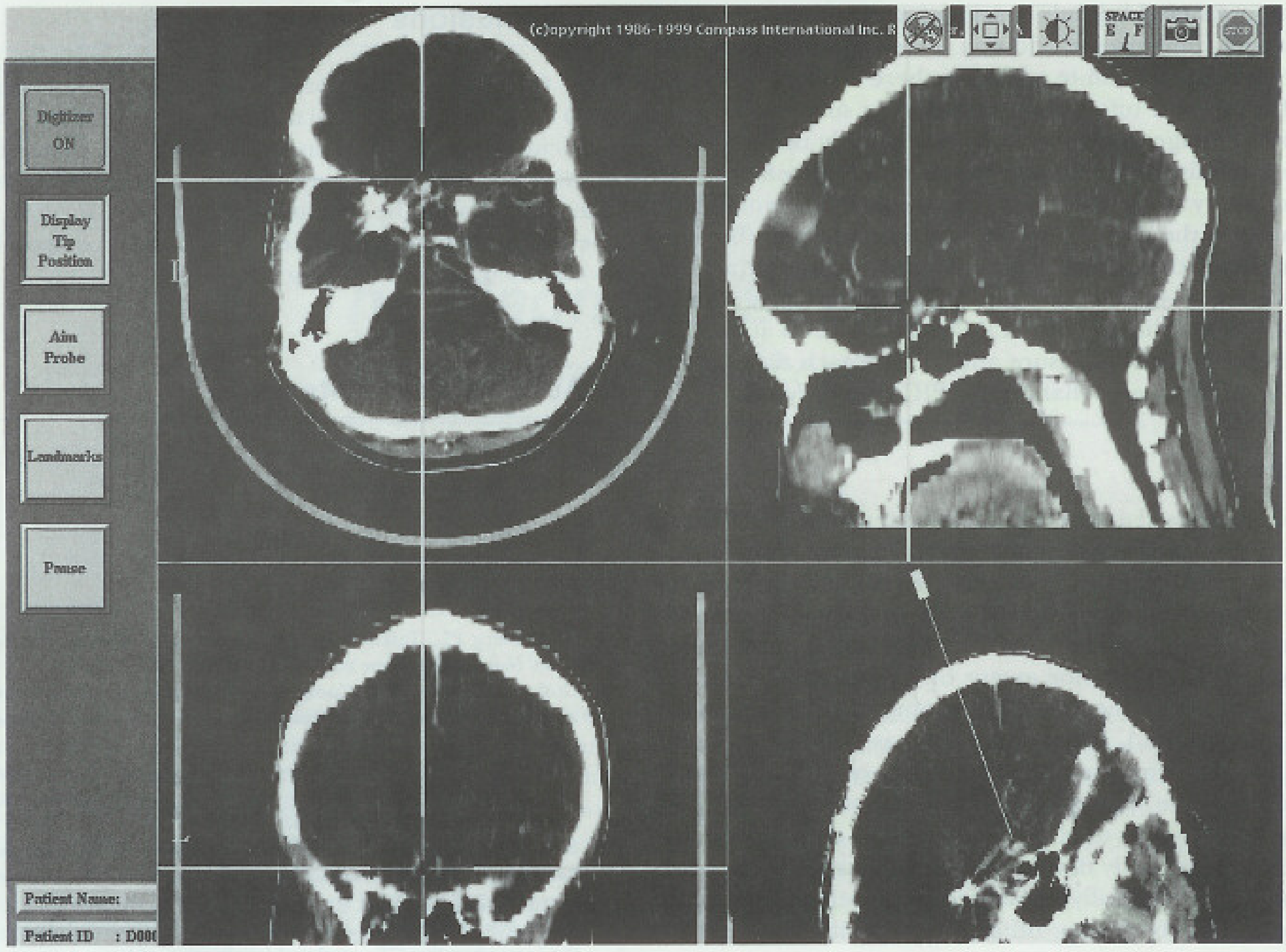

FIGURE 6–6. Intraoperative illustration of an interhemispheric approach to an unruptured anterior communicating artery aneurysm (ACom). The patient had prior surgery of a ruptured left middle cerebral artery (MCA) aneurysm with an ensuing left MCA stroke and aphasia that resolved over 1 year. The interhemispheric approach to the ACom artery was selected to avoid compromise of potentially tenuous speech cortex. The trajectory view is seen on the lower right.

of skull markers (fiducials) for all posterior fossa approaches.

Skull base

It may seem superfluous to employ image guidance for skull-base lesions. We have never regretted having image guidance available for these cases, however. Uses include defining the extent of a bone flap, determining the extent of skull-base bone drilling, and the avoidance of important structures such as arteries and nerves. We have also been using image guidance in lieu of fluoroscopy for transphenoidal approaches.

Vascular

Arterovenous malformations

We have used image guidance to ascertain the extent and depth of an arterovenous malformations (AVM) nidus has proven very useful. Stereotactic accuracy is usually maintained throughout the case because AVMs are best resected in one piece. Large feeding arteries and draining veins provide excellent intraoperative anatomical landmarks.

Cavernous angiomas

Cavernous angiomas are analogous to tumors when discussing the usefulness of image guidance. Guidance for localization is an issue for small or deep cavernomas, and again we recommend skull-implanted markers for these cases regardless of the type of image-guidance system used. For larger lesions, volumetric feedback is useful during surgery as with large tumors.

Aneurysms

Image guidance is rarely used during aneurysm surgery. We have found a number of indications that have proven useful and are linked to the advantages of the Cygnus-PFS magnetic system. Most vascular neurosurgeons would rightly consider image-guidance systems to be a cumbersome addition to aneurysm surgery. The Cygnus has a definite advantage here because of its ease of setup and unobtrusiveness during surgery. We have found image guidance to be particularly useful during interhemispheric approaches to anterior communicating artery aneurysms. In this situation, it is often difficult to assess the distance to the aneurysm despite the landmarks of the pericallosal and callosomarginal arteries (see Fig. 6–6). We have also employed image guidance to locate middle cerebral artery (MCA) aneurysms within the Sylvian fissure and to approach distal posterior inferior cerebellar artery (PICA) aneurysms.

Epilepsy

We have used image guidance extensively for lesional and nonlesional epilepsy surgery. In nonlesional cases, image guidance has been very helpful in defining a trajectory to find the temporal horn of the lateral ventricle in the context of selective amygdalo-hippocampectomies. The posterior extent of hippocampal resection and the superomedial extent of amygdalar resection can also be verified. Image guidance has also been a useful adjunct during functional hemispherectomies[13] and in defining the extent of corpus callosotomies. We have used the Cygnus to place intraoperative depth electrodes and are currently developing instrumentation for placement of chronically implanted depth electrodes as has been described using other image-guidance systems.[3,14]

Catheter placement

Placement of ventricular catheters with image guidance is not uncommon. The unobtrusiveness of the magnetic system has led us to use it relatively frequently to optimize routine shunt placement and also for placement of Omaya reservoirs.

■ Ear, Nose, and Throat

In combination with our ENT colleagues, we have used image guidance for approaches to the sphenoid and maxillary sinuses.

■ Ophthalmology

With our ophthalmological surgeons, we have used the Cygnus-PFS for image guidance during resections of orbital tumors with extraorbital invasion. They have also used the Cygnus for imaging feedback during lateral orbital decompressions for proptosis.

■ Conclusions

The Cygnus-PFS (Compass International, Rochester, MN) is a dedicated cranial image-guided system. It is particularly unobtrusive and lends itself to a number of cranial applications where other image-guidance systems would often be too cumbersome. The accuracy of the magnetic system has been shown to be comparable to that of an optical tracking system.

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