Clinical Use of the Optical Digitizer for Intracranial Neuronavigation

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Abstract
OBJECTIVE: Computer-assisted frameless navigation techniques are used in many centers for intracranial neurosurgical procedures. In this study, we assessed the accuracy and the clinical usefulness of a frameless system based on the optical digitizer in a variety of intracranial procedures.

METHODS: The optical digitizer (StealthStation, Sofamor Danek, Memphis, TN) was used to perform 170 neurosurgical operations. Its accuracy was judged before and after each operation by comparing the computer-estimated error with the real estimated error measured on the patient’s anatomy. Several objective factors were evaluated to assess the clinical usefulness of the optical digitizer. For craniotomies, the intraoperative extent of resection based on computer-generated images was compared with that on postoperative images, and the length of hospital stay of patients undergoing frameless procedures was compared with that of patients undergoing conventional procedures. For needle biopsies, clinical usefulness was based on the rate of success in establishing a histological diagnosis.

RESULTS: The optical digitizer was accurate to within 2 mm for all procedures. The computer-estimated error was not significantly different from the real estimated error. The intraoperative extent of resection was accurate in 58 of 60 tumor resection patients, as confirmed on postoperative images. Patients undergoing frameless procedures had a significantly shorter hospital stay than those undergoing conventional procedures (7.5 ± 1 versus 10.8 ± 1.3 d, P < 0.05). All biopsies were diagnostic.

CONCLUSION: The optical digitizer is an accurate frameless device that offers clinical benefits. These include precise surgical resection, decreased hospitalization time, and accurate tissue diagnosis.

Intracranial navigation is widely used in neurosurgery (5, 8–11, 20, 22, 23). Several systems have been described (3, 9, 13, 15, 16), and their accuracy has been documented in elegant reports (4, 12, 18, 25). Subjective comments by surgeons using these devices support neuronavigation as a useful adjunct to surgery. The most persistent question about frameless stereotactic devices, however, is whether they are accurate enough to meet the demands of neurosurgical procedures. Furthermore, there is concern that routine use of these devices might lengthen surgical procedures. Objective measures to evaluate neuronavigators are scarcely documented in the literature (6). With changes in managed health care, the cost-benefit issue of investment in high-technology equipment versus improvement in patient care is often raised.

In this study, we used objective criteria to evaluate the accuracy and usefulness of the frameless optical digitizer (OD) (9, 24) (StealthStation, Sofamor Danek, Memphis, TN) for intracranial neurosurgical procedures. Its accuracy was judged before and after each operation by comparing the computer-estimated error (CEE) of each registration with the real estimated error (REE). For craniotomies, the clinical usefulness was evaluated by comparing the extent of resection on intraoperative computer-generated images with that on postoperative images and by comparing the length of the hospital stay of patients undergoing frameless procedures with that of patients undergoing conventional operations. For brain needle biopsies, clinical usefulness was evaluated by the rate of success in establishing a histological diagnosis.

PATIENTS AND METHODS
Patient population
This retrospective study reviews the use of the OD for 170 consecutive intracranial operations performed by a single surgeon (IMG) between May 1995 and September 1998. Before the StealthStation was approved by the United States Food and Drug Administration (January 24, 1996), a signed informed consent approved by our institutional review board was obtained in each case.

Neuronavigation equipment

The OD system has been described in detail elsewhere (9, 24). It consists of a computer workstation and monitor, software, a digital audiotape driver, an OD, a reference arc, and an optical camera system (Fig. 1). The system is based on an OD and light-emitting diodes (LEDs) attached to surgical instruments (Bucholz free-hand technology) (24). The position of each LED is monitored by three cameras that send real-time feedback to a computer. In this way, the position of the instruments in relation to any intracranial structure can be displayed instantly.

Preoperative data acquisition

Preoperatively, computed tomography (CT) or magnetic resonance imaging (MRI) was performed after 8 to 12 multimodality adhesive markers (IZI Medical, Baltimore, MD) were placed in a noncolinear fashion on the patient’s head. The skin was marked with indelible ink through a hole in the center of each marker and around its perimeter to monitor for potential movement. In most cases, imaging studies were obtained on the morning of the procedure.

For computed tomographic studies, continuous nonoverlapping 2-mm-thick axial slices were obtained without gantry tilt and with a 512 × 512-pixel data set. For MRI studies, continuous nonoverlapping 2-mm axial slices of constant thickness were obtained without interspacing and with a 34-cm field of view, a 256 × 256 matrix, and a single echo (echo time, 14 ms; repetition time, 600 ms).

Surgical planning

The images were archived on a digital audiotape in GE format and subsequently loaded into the OD; image transfer by ethernet is currently being implemented. The OD computer reformatted the axial images into coronal and sagittal views and three-dimensional (3-D) images. The three-planar images can be viewed in real time in each of the three planes. On the 3-D images, different structures can be assigned different colors or degrees of transparency (typically skin, bone, ventricles, lesion), and a transparent window can be overlaid to view subcutaneous structures. The 3-D reconstruction can be cut by an orthogonal or oblique wedge and rotated to provide the best angle to visualize the anatomy of interest. The computer can also reformat images in the same plane as the surgical instrument (pointer or bipolar cauterizer); these “trajectory views” are orthogonal or perpendicular to the instrument (Fig. 2).
FIGURE 2. Intraoperative photograph of the computer screen displaying the surgical plan for a frameless stereotactic biopsy. After acquisition of axial images, the computer reformats coronal, sagittal, and 3-D images. Images perpendicular (Traj. View 1) or orthogonal (Traj. View 2) to the surgical instrument with LED are reformatted. These are particularly helpful to allow correct orientation during microsurgical resection or placement of the biopsy needle.

Surgical planning was conducted in the operating room while the patient was undergoing anesthesia. Typically, we selected an entry point on the skin and a target within the lesion. These points were represented on the screen by a hollow yellow cylinder, and the computer calculated the distance between the two points. Moving the cursor along the planned surgical path indicated by the yellow cylinder allows the surgeon to simulate the surgery and visualize structures that will be encountered. The pathway can be modified preoperatively as needed. The software provides other views of the selected surgical plan from a surgeon’s perspective.

Intraoperative procedures

All craniotomies were performed with the patient under general anesthesia. All biopsies, functional procedures, and ventricular access procedures were performed with intravenous sedation. The patient’s head was routinely immobilized in a Mayfield headrest system (OMI, Inc., Cincinnati, OH); when general anesthesia was not used, the head holder was applied after injection of 1% lidocaine into the scalp. Care was taken to apply the head holder at least 2 cm away from the adhesive markers to avoid skin movement.

A rigid mechanical connection was established between the head holder and the reference arc. Care was taken to avoid positioning the reference arc in the surgeon’s working space. For craniotomies, the arc was placed approximately 30 cm anterior to the patient’s head; for brain needle biopsies, it was placed approximately 20 cm posterior to accommodate the self-retaining retractor holder for the biopsy instruments.

Registration was performed as described below, the scalp was then prepared using sterile technique. If one of the adhesive markers was in the preparation field, it was removed. The reference arc was then removed, and the head was draped with a transparent plastic drape (Radionics, Burlington, MA) [2] to allow the markers to remain visible in case reregistration was necessary.

Minimizing error from brain shift

To minimize error resulting from brain shift, we adopted several measures that deviate from classic tumor resection technique. First, neither mannitol nor diversion of cerebrospinal fluid was used routinely. Patients undergoing craniotomy were hyperventilated throughout the operation (pCO₂, 22–25 mm Hg). If the brain was tense, a small bolus of mannitol (0.5 g/kg) was administered intravenously before the dura was opened. Second, intraparenchymal tumors were resected en bloc to minimize the amount of tissue shift that occurs after typical centipetal resection [19]. Finally, extreme positioning (full lateral, full flexion-extension) of the head was avoided to minimize shift and to facilitate the interpretation of the real-time feedback on the computer images.

Registration
Once the patient was positioned appropriately for the planned surgical procedure, the patient’s anatomy was registered by establishing spatial correspondences between the patient’s head and the acquired images. In all cases, “point-to-point” registration was used, in which the adhesive markers on the patient’s head were localized with the LED pointer, and the corresponding landmarks on the computer images were localized with a mouse-driven cursor. This process proceeded counterclockwise from marker to marker.

During marker registration, the computer processed the manually located point pairs. The computer then estimated the registration transformation required to align the images with the patient’s anatomy. Conceptually, the solution of this problem is equivalent to attaching “springs” between pairs of corresponding points (i.e., the image points and the digitizer points). Collectively, these springs are allowed to transform the two-point sets relative to each other by pulling along the spring axes. The registration transformation is estimated by determining the final resting position of this spring system. A measure of the error in this transformation can be computed from the distances between the pairs of corresponding points after the spring system has converged. The measure used in these studies, the mean fiducial error, or CEE, is the average of these distances, which provides an estimate of the quality of the registration. A CEE was considered acceptable if it was 4 mm or less for craniotomies and 2 mm or less for the other procedures.

In 15 patients, facial features were used to perform a second registration. The anatomic landmarks used for facial registration included the tragus, the medial and lateral canthi, nasion, glabella, and any other salient feature such as scars from previous surgeries. Facial registration consisted of pointing to the same anatomic features on the patient’s head and on the computer images. The facial registrations were then compared with the marker registrations.

In 10 patients, facial registration was followed by a “surface-based” registration. This process aligns two surface representations of the patient’s head, one constructed from the preoperative images and one from 3-D point data collected with a pointer before surgery. Conceptually, surface-based registration is similar to placing a tight-fitting helmet onto the patient’s head. Surface-based registration uses the transformation established by point-to-point registration as a starting point. For surface registration, approximately 40 points on the head are randomly chosen within the scanned volume, digitized, and stored in the computer. A geometric model of the surface of the patient’s head is constructed from the acquired images. The computer then aligns the geometric model with the 40 points by finding a transformation that minimizes the error between them. In surface-based registration, an error measure based on the distances between each of the digitizer points and the geometric surface model can be used to estimate the quality of the registration. The time necessary for each registration was noted when it exceeded 15 minutes for “point-to-point,” 30 minutes for facial, and 45 minutes for surface-based registration.

Evaluation of accuracy

The accuracy of the OD was measured before and after each procedure. In addition, after the bone flap was open, the pointer was used to localize one or two markers. If gross movement (>=2 mm) was detected, the registration was repeated. This was possible because the markers were clearly visible through the transparent drape.

At the beginning of the procedure, the CEE was recorded after each registration. After the registration was completed, the REE was calculated by positioning the tip of the LED pointer in the center of a marker. Crosshairs indicating the real-time location of the pointer on the patient’s head appeared on the reformatted images. The distance between the crosshairs and the center of the marker on the reformatted images was measured by the computer on the three-planar images. This measured distance was calculated for at least three markers, and the mean was recorded as the REE for each patient. The CEE and REE of each of the three registration techniques used (markers, facial landmarks, and facial surface) were compared within and across registrations.

Evaluation of clinical usefulness

The clinical usefulness of the OD was assessed subjectively at the time of surgery. This assessment was based on the flap size, accuracy of the flap location over the tumor, ease of microsurgical dissection, avoidance of critical structures, location of the lesion, and definition of margins.

The clinical usefulness was assessed objectively by monitoring different factors according to the type of procedure. For craniotomies, the intraoperative extent of resection on computer-generated images was compared with that on postoperative images, and the length of hospital stay of patients undergoing frameless procedures was compared with that of patients undergoing conventional procedures. For needle biopsies, clinical usefulness was assessed by the rate of success in establishing a histological diagnosis.

The extent of resection was determined by the surgeon from the intraoperative images. Gross total resection of enhancing tumors was defined as removal of the area of hyperintense signal on contrast-enhanced T1-weighted images. Gross total resection of nonenhancing tumors was defined as removal of the circumscribed
area of hypointensity on T1-weighted images or hyperintensity on T2-weighted images. For subtotal resections, the amount of residual tumor was graded semiquantitatively (<=25%, <=50%, and <=75% of total tumor), and the site of residual tumor with respect to the bulk of the lesion was noted (anterior/posterior, inferior/superior, medial/lateral).

The intraoperative extent of resection was confirmed by postoperative CT or MRI before and after administration of contrast material within 48 hours of surgery. The extent of resection shown on postoperative images was graded as described above in a blinded fashion by the neuroradiologist (AS).

For the period from May 1995 to September 1997, the length of hospital stay of patients who underwent craniotomy for resection of intra-axial supratentorial brain tumors with frameless stereotaxy was compared with that of 52 consecutive patients who underwent conventional craniotomy by 12 different surgeons at our institution.

For brain needle biopsies, clinical usefulness was based on the rate of success in establishing a histological diagnosis. In all cases, an unenhanced computed tomographic scan of the head was obtained to exclude hemorrhage and confirm the location of the biopsy within the lesion. For ventricular access procedures, clinical usefulness was based on the success of establishing access at the first attempt; correct positioning of the intraventricular catheter was confirmed by postoperative CT or MRI.

Statistical analysis

Data are expressed as means ± standard deviation. An unpaired Student’s t test was used to compare CEE and REE within each registration type and to compare the length of the hospital stay. Analysis of variance with Bonferroni’s posthoc comparison was used to compare CEE and REE across registration types. A paired Student’s t test was used to compare CEE and REE before and after surgery.

RESULTS

Surgical cases

The OD was used to perform 170 intracranial neurosurgical procedures: 86 craniotomies for tumor resection, 65 needle biopsies, 7 ventricular access procedures, 1 craniotomy for aneurysm clipping, and 11 functional procedures. In the latter 11 patients, the OD was used in conjunction with a rigid frame (Cosman-Roberts-Wells frame; Radionics). There were 69 women and 101 men in this study; their mean age was 53 ± 2 years (range, 5–88 yr). The histological diagnoses are summarized in Table 1.

TABLE 1. Histology of Craniotomy and Biopsy Procedures

<table>
<thead>
<tr>
<th>Tumor Type</th>
<th>Craniotomy</th>
<th>Biopsy</th>
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<tbody>
<tr>
<td>Metastasis</td>
<td>22</td>
<td>8</td>
</tr>
<tr>
<td>Glioblastoma</td>
<td>27</td>
<td>18</td>
</tr>
<tr>
<td>Glioma</td>
<td>23</td>
<td>18</td>
</tr>
<tr>
<td>PML&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Lymphoma</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Others&lt;sup&gt;b&lt;/sup&gt;</td>
<td>14</td>
<td>4&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total</td>
<td>86</td>
<td>65</td>
</tr>
</tbody>
</table>

<sup>a</sup> PML, progressive multifocal leukoencephalopathy.
<sup>b</sup> Hamartoma, 1; meningioma, 6; cavernous angioma, 2; infections, 5.
<sup>c</sup> Toxoplasmosis, 2; abscess, 1; germinoma, 1.

Registration using the adhesive markers did not substantially prolong the length of the surgical procedures. This was performed in 15 minutes or less in each procedure. Registration using facial landmarks was longer, requiring up to 30 minutes, as it is more difficult to match anatomic features to those seen on the images. When surface-based registration was used, the total registration time took up to 45 minutes.

Accuracy of registration
The registration data are summarized in Table 2. Although 8 to 12 adhesive markers (fiducials) were placed on each patient, those too close to the head holder or difficult to reach with the pointer were not used for registration. Fewer registrations were required to achieve an accuracy of 2 mm or less with CT than with MRI. Furthermore, registrations with computed tomographic scans were more accurate than those with MRI scans. However, these differences were not significant. Postoperative validation of the registration error was not significantly different from the preoperative validation. There were no differences in the CEE and REE before or after surgery.

### TABLE 2. Registration Data in 106 Patients (Mean ± SE)\(^a\)

<table>
<thead>
<tr>
<th></th>
<th>CT (n = 23)</th>
<th>MRI (n = 83)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducials used</td>
<td>5 ± 0.3</td>
<td>5.3 ± 0.2</td>
</tr>
<tr>
<td>Registrations</td>
<td>3 ± 0.6</td>
<td>3.4 ± 0.4</td>
</tr>
<tr>
<td>CEE before surgery</td>
<td>1.8 ± 0.1</td>
<td>1.9 ± 0.1</td>
</tr>
<tr>
<td>CEE after surgery</td>
<td>2 ± 0.2</td>
<td>2 ± 0.2</td>
</tr>
</tbody>
</table>

\(^a\) SE, standard error; CT, computed tomography; MRI, magnetic resonance imaging; CEE, computer-estimated error in mm.

Table 2. TABLE 2. Registration Data in 106 Patients (Mean ± SE) \(^a\) SE, standard error; CT, computed tomography; MRI, magnetic resonance imaging; CEE, computer-estimated error in mm.

Table 3 summarizes the CEE and REE obtained with three different registration processes: markers, facial, and facial followed by surface (see Patients and Methods). Point registration was the most accurate. The use of the surface-fitting algorithm significantly improved the accuracy of facial registration (\(P < 0.05\)). However, the REE of this technique was still larger than that of marker registration. There was no significant difference between CEE and REE in any of the three registration types.

### TABLE 3. Computer-estimated Error and Real Estimated Error Established by Markers, Facial Landmarks, and Facial Surface Registration Techniques\(^a\)

<table>
<thead>
<tr>
<th>Registration Error (mm)</th>
<th>CEE</th>
<th>REE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Markers</td>
<td>1.8 ± 0.1(^b)</td>
<td>1.7 ± 0.2(^c)</td>
</tr>
<tr>
<td>Facial landmarks</td>
<td>2.9 ± 0.2</td>
<td>3.4 ± 0.2</td>
</tr>
<tr>
<td>Facial surface</td>
<td>1.9 ± 0.2</td>
<td>2.3 ± 0.3</td>
</tr>
</tbody>
</table>

\(^a\) CEE, computer-estimated error; REE, real estimated error.

\(^b\) Analysis of variance (2,63) \(F = 5.821; P = 0.005\).

\(^c\) Analysis of variance (2,63) \(F = 26.6; P < 0.0001\).

Clinical usefulness: subjective assessment

The OD was useful for planning the craniotomy in all patients. Preoperative review of the three-planar images allowed the surgeon to devise a minimally invasive procedure by avoiding eloquent areas of the brain, vascular structures, and air sinuses. In all patients in whom the flap was designed before the tumor was localized by neuronavigation, use of the OD resulted in a smaller flap at surgery. The neuronavigator was also helpful in locating small, deep-seated lesions such as metastases and cavernous angiomas. For primary brain tumors, the OD was helpful in establishing tumor boundaries before resection and in determining the extent of resection. Finally, displaying the planned surgery before its execution was a valuable training experience for residents.

Clinical usefulness: objective assessment

Extent of resection

Gross total resection determined on intraoperative images was confirmed by postoperative images in all 22 patients undergoing craniotomy for brain metastasis, 6 patients with meningiomas, 2 patients with cavernous angiomas, and 5 with other intra-axial lesions (Table 1).
Gross total resection (as defined in Patients and Methods) was measured intraoperatively in 22 patients with gliomas. This was confirmed by postoperative images in 31 patients (Fig. 3). In two patients, linear enhancement compatible with residual tumor in the posteromesial temporal region was seen on postoperative images.

Subtotal resection was measured intraoperatively in 18 patients with gliomas. In 17 of these patients, the extent of resection and location of residual tumor was correctly measured intraoperatively. In one patient with a large left peri-sylvian anaplastic astrocytoma, postoperative images showed more residual tumor than was measured intraoperatively (25–50% versus <=25%).

These results with gliomas were obtained by using different strategies with the OD. Before resection of gliomas abutting the cortex, the system was used to demarcate the perimeter of the lesion by touching the cortex with the Bucholz bipolar cauterizer and observing its real-time position on the computer-reformatted images; the edges of the lesion were marked with silk thread. Cottonoids were advanced in a “fence post” fashion to the depth of the tumor with a technique similar to that described by Hassenbusch et al. (14); the lesion was then resected, as described (19). The extent of resection was corroborated by additional adjacent landmarks, such as tentorial edges or ventricular surface, to minimize the inevitable error resulting from brain shift and resection.

FIGURE 3. A 53-year-old man presenting with right hemiparesis and seizures. A, axial MRI brain image after contrast medium administration at the time of presentation, showing a large, poorly enhancing left frontal lesion. The patient underwent a computer-assisted gross total resection, and histology revealed a ganglioneurocytoma. Postoperative axial brain magnetic resonance images (B, before contrast; C, after contrast) 1 year after the resection, confirmed gross total resection.
For deep-seated lesions, the OD was used to identify the sulcus nearest to the lesion for a transsulcal approach (Fig. 4). A corticectomy in the depth of the sulcus was performed, and the system was then used to navigate to the lesion during the microsurgical dissection (Fig. 5).

FIGURE 4. A 69-year-old man with a history of lung adenocarcinoma. As part of his workup, he underwent a brain MRI examination, which revealed a right temporoparietal lesion. A, intraoperative photograph of the computer screen displaying the reformatted images (on the screen, left and right images are displayed reversed from conventional MRI) at the time of microsurgical dissection. The crosshairs indicate the real-time position of the bipolar cauterizer (B) over the sulcus chosen for the transsulcal approach. C, intraoperative photo of the cortex at the end of the surgical resection. D, resected lesion. Histology confirmed adenocarcinoma.
Needle biopsy, catheter placement, and functional procedures

All 67 brain needle biopsies performed were diagnostic. The mean maximal longitudinal diameter of the lesions biopsied was 3.5 ± 1.1 cm (range, 1.5–6.3 cm). Accurate placement of ventricular catheters was confirmed on postoperative images in all three patients. The three-planar displays were helpful in choosing the trajectory for the implanted electrode, and they allowed us to visualize the 3-D anatomy of the aneurysm. The clinical usefulness of the OD during the functional procedures will be reported in detail elsewhere.

Hospital stay

The length of the hospital stay after resection of intra-axial tumors was compared in patients who underwent conventional (n = 52) or frameless (n = 50) procedures. The age and sex of these patients and their tumor histologies are summarized in Table 4. All patients had a Karnofsky score over 50. The hospital stay was significantly shorter among patients who underwent frameless stereotactic craniotomy than among those underwent conventional craniotomy: 7.5 ± 1 compared with 10.8 ± 1.3 days, respectively (unpaired Student’s t test: t(100) = -2.09; P = 0.0393). There was no significant difference in age, sex, or tumor histology between the two groups.
TABLE 4. Age, Sex, and Tumor Histology of Patients Undergoing Frameless or Conventional Neurosurgical Procedures

<table>
<thead>
<tr>
<th></th>
<th>Frameless (n = 50)</th>
<th>Conventional (n = 52)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (yr)</td>
<td>54 ± 2</td>
<td>57 ± 2</td>
</tr>
<tr>
<td>Sex (M/F)</td>
<td>30/20</td>
<td>22/30</td>
</tr>
<tr>
<td>Tumor histology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metastasis</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>Glioblastoma</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>Glioma</td>
<td>16</td>
<td>11</td>
</tr>
</tbody>
</table>

Associated complications

No adverse effects were attributable to the use of the OD. Technical problems were experienced in six procedures. In two procedures, an accuracy check performed after the craniotomy was completed but before microdissection had begun showed significant movement. In both instances, reregistration was easily accomplished, as the markers were clearly visible through the drape. In one case, the equipment was accidentally unplugged during microdissection, and the registration was lost. At that point, we continued the surgery with standard techniques, as we were already near the lesion. Subsequently, the software was modified to include instantaneous saving of the registration in the case of power interruption. In two instances, the markers were accidentally removed before surgery; however, the indelible marks made before imaging (see Patients and Methods) and additional facial landmarks permitted reregistration. In the first biopsy case, the reference arc was positioned too far from the patient’s head. As a result, the self-retaining arm could not be used, and the biopsy arm was held manually. Nonetheless, the biopsy was diagnostic.

DISCUSSION

Accuracy

There are several reports on the accuracy of frameless navigational systems (4, 12, 17, 18). In particular, the accuracy of the OD under optimal conditions in the laboratory compares favorably with that of four commonly used conventional stereotaxy systems: Brown-Roberts-Wells and Cosman-Roberts-Wells (Radionics), Leksell (Elekta Instruments, Inc., Atlanta, GA), and Kelly-Goerss (Stereotactic Medical Systems, Rochester, MN) (7, 21). To establish accurate frameless coordinates, well-defined, easily recognizable fiducials are necessary. Slight errors in selecting the precise location of fiducials with the LED pointer can result in significant transformation errors. Further error can occur with adhesive markers because they can move on the scalp. Some surgeons use implantable fiducials (i.e., percutaneous bone screws) to avoid this error. This is more invasive before the craniotomy, however, and we have not found it necessary in our practice (11). Despite these sources of error, in our experience the accuracy of the OD was sufficient for any open neurosurgical procedure or intracranial diagnostic biopsy for lesions larger than 1.5 cm. At the present time, we would not use this system without conventional stereotaxy for functional procedures.

Frameless stereotaxy offers some advantages over frame-based stereotaxy (9), yet application of the fiducial markers on the scalp remains somewhat tedious. Furthermore, although imaging studies are usually part of the initial diagnostic workup, they must be repeated with the markers in place. To avoid redundant imaging, facial landmarks have been used for registration. However, because it is more difficult to determine the exact location of facial landmarks on the computer images, this method is more prone to error than marker-based registration. Thus, the addition of a surface-based algorithm to the registration technique could potentially improve the accuracy of the facial registration procedure. Our results showed that surface-based registration can be used for localization, but it is less accurate than point registration with markers, as reported previously (25). In most of our cases, patients have undergone imaging studies at hospitals where the protocol necessary to interface the images with the neuronavigator was not followed. Thus, even if we were to use facial landmarks for registration, it would be necessary to obtain a preoperative MRI scan using the protocol described under Patients and Methods. Therefore, we continue to perform registration with markers. If accuracy within 2 mm is not a critical factor, however, facial landmarks can be used if the patient has already been scanned with images compatible with the neuronavigator.

Subjective clinical usefulness

Neuronavigation provides a real-time virtual linkage between digitized neuroradiological images and anatomic structures. This allows an excellent 3-D orientation by real-time graphic-anatomic interaction. In our...
study, we found the OD helpful in surgical planning and microsurgical dissection, as reported previously for other neuronavigators (4, 12). Furthermore, displaying the planned surgery before its execution was a valuable training experience. Finally, the OD is user-friendly and does not require a dedicated technician to perform the data reconstruction and intraoperative registration.

Objective clinical usefulness

Most studies on the clinical usefulness of neuronavigation rely on subjective statements of neurosurgeons using the system (12, 25). Our study addresses the objective usefulness of neuronavigation. Several factors can be assessed to measure clinical usefulness. Without neuronavigation, the neurosurgeon’s intraoperative estimate of gross tumor resection agrees with that determined from postoperative images only one-third of the time (1). In this study, the intraoperative extent of resection determined with the OD agreed with that determined from postoperative images in 58 of 60 patients (97%). We believe that this high degree of concordance reflects the use of surgical techniques to minimize brain shift during resection of large tumors. Nonetheless, the lack of real-time updating of preoperative images is a limitation of frameless and frame-based stereotactic systems, both of which are subject to errors resulting from brain shift. In this series, such errors occurred in two patients.

In one case, a large temporal lobe tumor was thought to have been totally resected. Postoperative images showed a linear enhancement of the posteromedial border, consistent with residual tumor. To compensate for brain shift resulting from tumor resection, reregistration on “fixed” structures, such as the free edge of the tentorium (22), is possible. This requires good experience with neuronavigation. Because this was the third patient in this series, we were still on a steep learning curve. In the other patient, who had a very large, deep perisylvian glioma, brain shift occurred as a result of both tumor resection and brain retraction necessary for microsurgical dissection to open the sylvian fissure. Further developments in neuronavigation are needed to facilitate real-time assessment of the extent of surgical resection.

Ongoing changes in managed care are pressuring physicians to shorten hospital stays to reduce costs. In our study, use of neuronavigation significantly decreased the length of hospitalization (7.5 ± 1 versus 10.8 ± 3 d). We hypothesize that the shorter hospital stay is attributable to less invasive procedures, resulting in decreased perioperative morbidity and faster recuperation. This hypothesis is currently being tested in a prospective study.

The diagnostic yield of brain needle biopsies with frame-based technologies ranges from 92 to 100% (2). In our study, all 67 needle biopsies performed were diagnostic. However, lesions with a maximal diameter of 1.5 cm or less were not biopsied with frameless technology. Thus, for routine brain tissue sampling, a histological diagnosis can be obtained with frameless stereotaxy. Further experience with the use of frame-based and frameless systems in combination is needed to ascertain whether frameless guidance alone would provide accurate histological diagnosis of smaller lesions.

CONCLUSIONS

Neuronavigation with the OD during intracranial procedures is accurate to within 2 mm. Although the lack of real-time updating of preoperative images is currently a limitation of stereotactic devices, steps can be taken to reduce intraoperative brain shift. In our study, neuronavigation provided helpful guidance for gross total resection of small, deep-seated lesions and larger gliomas, as well as for routine histological diagnosis. Furthermore, neuronavigation significantly shortened the hospital stay. As frameless graphic-interactive navigation is developed further, it will become an invaluable neurosurgical tool.

ACKNOWLEDGMENT

Dr. Isabelle M. Germano serves as a consultant for the Surgical Navigation Division of Medtronic Sofamor Danek in Broomfield, CO.

REFERENCES


COMMENTS

The authors report their experience in 170 intracranial procedures using a popular surgical navigation system. The system proved to be accurate using their methods of measurement and was certainly sufficient for open intracranial surgery. The extent of the resection that they were able to achieve was similar to that reported using other commercially available systems (2). They also found that patients appeared to have a shorter hospital stay than a cohort of patients operated on by other surgeons during the same period.

The use of surgical navigation systems has become a mainstay in contemporary intracranial neurosurgery. The results of this article are consistent with those obtained and presented elsewhere using other systems. It is important to note that excellent results were obtained by using conventional strategies to minimize the impact of "brain shift," as has been described by Kelly (1) and others. These results argue that elaborate methodology to correct for brain shift is probably not warranted in most cases.

As with any nonrandomized study, the conclusions regarding length of stay and socioeconomic issues remain suspect. It would appear unlikely that such a study could be performed now, however, because of a perception that this technology results in overall better outcomes at the same or lower morbidity. It is unfortunate that the authors did not compare the conventional versus surgical navigation-assisted craniotomy groups using one of the recently proposed grading systems to assess surgical outcomes (3, 4). This would allow a better assessment of comparability. As it stands, there appear to be a higher number of glioblastoma patients in the conventional group and a lower number of other gliomas, which may unfavorably bias the conventional craniotomy group. Nor is it clear whether other risk factors, such as lesion location (eloquent, deep) and previous radiation, were comparable between the two groups. Nonetheless, the paper provides further evidence that surgical navigation is an important adjunct in the management of patients with intracranial tumors.

Gene H. Barnett

Cleveland, Ohio


Computer-assisted neuronavigation is becoming an increasingly important part of the neurosurgical planning and performance of both intracranial and intraspinal surgery. The authors describe their experience with the optical digitizer. The small amount of time invested in obtaining the images and setting up the equipment is clearly worthwhile intraoperatively. I have extensive experience with the StealthStation (Sofamor Danek, Memphis, TN), Easy Guide (Philips Medical Systems, Eindhoven, The Netherlands), and ISG (Elekta Instruments, Inc., Atlanta, GA). My favorite is the StealthStation. Even a very simple removal of a convexity meningioma can be planned to minimize the scalp flap and bone flap required to completely remove it. Important adjacent structures, such as sinus and major arteries, can be identified, marked, and spared. Within the depths of a tumor, neuronavigation is extremely useful. However, it must be tempered by experience and the constant concern that structures may shift. Real-time updating of intraoperative shifts remains a critical need. Even in epilepsy cases, in which there is no physical structure to be removed, I find it helpful for documentation of the location of subdural electrodes. It is of considerable interest that the authors plan a prospective study to examine the length of hospital stay and perioperative morbidity for the standard neurosurgical procedures versus those using neuronavigation. In the future, it will be very important to prove the added value of these expensive techniques.

Roy A. E. Bakay
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Germano et al. make a valuable contribution to the frameless stereotaxy literature through their documentation of the accuracy and usefulness of one such system in 170 neurosurgical procedures. Estimated accuracy of approximately 2 to 3 mm was achieved; from a practical standpoint, this precision is certainly satisfactory. That they achieved their surgical objective of intended extent of resection in nearly all patients, or of diagnosis in the cases of biopsy, confirms this.

In each patient, they used 8 to 12 adhesive fiducial markers for registration and recorded a computer-estimated error (goodness of fit between two arrays of paired points) and a real estimated error (the mean of a least three measurements of the distance between a test point and its image coordinate space location). In a subset of cases, they also used natural landmarks and surface registration, enabling a comparison of methodologies. It is possible for a goodness of fit estimate (their computer-estimated error) to be excellent but for true accuracy to be lower, as would happen were there a bias error in the localization of each fiducial. One could envision such an error arising from a distorted imaging study or a faulty digitizer. For this reason, an estimate of accuracy using an actual test point is complementary and useful. In this reported experience, that this error was not much larger provides reassurance that such a bias error was not problematic. Ideally, a surgeon would use a test point independent of those fiducial points used for the registration itself, but for the above reason, it can still be a useful measurement.

True accuracy is also dependent on the geometric relationship between the region of surgical interest and the fiducial array. Accuracy will not be uniform throughout the intracranial volume, and in the undesirable event that a region of surgical interest is distant from a nonsurrounding array of fiducials (e.g., anteriorly located fiducials and a posterior tumor), a lever-arm effect can produce error significantly greater than either the computer-estimated error or real estimated error as measured in this report. For all of these reasons, it is a good idea for surgeons to have at least a basic understanding of the principles underlying this methodology.

Although I share the authors’ belief that the use of neuronavigation tools will lead to more efficient and cost-effective surgery, the comparison in this report of length of stay for these patients with that of 52 patients who underwent conventional craniotomies by other surgeons at their institution is harder to interpret. Although a significant difference was observed, the comparison illustrates the need for prospective, randomized, and double-blind methodology: we do not know whether those patients were older, were sicker, underwent more extensive procedures, had slower surgeons, or were less motivated to go home.

David W. Roberts
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Key words:: Computer-assisted surgery; Frameless stereotaxy; Neuronavigation; Optical digitizer; Stereotaxy
TABLE 1. Mixology of Craniotomy and Ring Procedures

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Number</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Craniotomy</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Gliomas</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Meningiomas</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>Suprasellar</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Hypothalamus</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Others</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

Note: Mixology refers to the combination of craniotomy and ring procedures.


<table>
<thead>
<tr>
<th>Technique</th>
<th>Computer-aided Error</th>
<th>Real Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR</td>
<td>1.9 ± 0.1</td>
<td>3.9 ± 0.2</td>
</tr>
<tr>
<td>CT</td>
<td>3.5 ± 0.2</td>
<td>5.4 ± 0.5</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>2.9 ± 0.1</td>
<td>5.8 ± 0.3</td>
</tr>
</tbody>
</table>

Note: Computer-aided error refers to the error calculated using computer-assisted navigation systems.

TABLE 3. Age, Sex, and Type of Malignancy of Patients Undergoing Treatment of Cerebral Neoplasms

<table>
<thead>
<tr>
<th>Age Range</th>
<th>Gender</th>
<th>Malignancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-25</td>
<td>Male</td>
<td>10</td>
</tr>
<tr>
<td>26-35</td>
<td>Female</td>
<td>12</td>
</tr>
<tr>
<td>36-45</td>
<td>Male</td>
<td>15</td>
</tr>
<tr>
<td>46-55</td>
<td>Female</td>
<td>8</td>
</tr>
</tbody>
</table>

Note: The table presents the age range, gender, and type of malignancy of patients undergoing treatment for cerebral neoplasms.

FIGURE 1: Illustration of the optical digitizer system.

FIGURE 2: Comparison of computer-aided error and real error in navigation.


FIGURE 4: Example of navigation system output.

FIGURE 5: Detailed view of the optical digitizer in use.