Frameless Stereotaxy of the Brain

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Abstract

Today's neurosurgical journals are replete with advertisements for systems designed to provide image guidance during surgery. These so-called "frameless" stereotactic systems provide the surgeon with navigational information, relating the location of instruments in the operative field to preoperative imaging data. Such information minimizes invasiveness by more accurately selecting the best trajectory to the lesion, ensures more precise identification of normal structures, and guides complete removal of a lesion. To achieve these goals, all of these systems utilize the stereotactic principle of co-registration of the patient with an imaging study.

This review will trace the development of image-guided surgery from its origins in frame-based stereotaxy to its current use as a surgical navigation methodology. A review of the more prevalent techniques and available systems will be presented, along with examples of specific applications of surgical navigation. Finally, some of the future directions of frameless stereotaxy will be discussed.

Key Words: Computer-assisted surgery, image-guided surgery, stereotaxy.

Historical Background

EARLY STEREOTACTIC SYSTEMS used a frame to satisfy the need for accurate co-registration and probe guidance. By fixing a frame to the head, Horsley and Clarke (1) were able to define a coordinate system in space that effectively included the intracranial contents. This defined space could then be related to a known atlas of the brain, and a probe could be directed to a specific site within the defined space. This proved to be a useful laboratory technique, but did not take into account normal anatomic variation. It was not immediately extended to clinical practice.

Co-registration of frame-defined space with an individual imaging study followed. With the frame in place during the radiologic exam, imaged anatomic structure was located in the frame's coordinate system. This technique was limited by the information discernible on plain radiographs, pneumoencephalography, positive contrast encephalography and, later, angiography, so reference to co-registered atlases was still necessary. The location of structures not appearing on the image, such as the ventrolateral nucleus of the thalamus, could be inferred by their known relationships to structures that were visible, such as the anterior and posterior commissures. The advent of computerized tomography significantly improved the anatomic localization of specific structures and their interrelationships. Calculations to direct a probe to a specific site seen on the study were simplified, and more intracranial structures were directly visualized. Not surprisingly, application of the methodology to biopsy tumors became widely popular. Atlas relationships were still necessary for the location of less well visualized structures, such as the nuclei of the thalamus, but the accuracy and ease of the calculations determining these relationships in the defined coordinate system were considerably improved. With the introduction of magnetic resonance imaging and its still greater resolution, the need for atlas relationships was further reduced;

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many conventionally targeted intracranial structures are now directly visible on the imaging study.

With all of this imaging information available, it became clear that the application of stereotactic technique held far more promise than had previously been realized. Adequate mapping data was available to guide the surgeon directly to a lesion or structure. The location of normal structures could be identified with greater accuracy, enhancing the ability of the surgeon to avoid injury to these structures. Finally, by co-registering the surgical field and instruments with a fully three-dimensional imaging study, the exact location of instruments within the field could be determined, which in turn allowed greater confidence in the extent of a lesion's resection.

Development of Frameless Stereotactic Systems

The stereotactic frame had been essential to the conceptualization of stereotactic technique because it was the tool through which co-registration and instrument guidance were achieved. The stereotactic frame is limiting, however, in a number of respects. It generally provides targeting of only a single point rather than orientation to three-dimensional anatomy. Further, it functions primarily to direct a probe to a preselected target, not to find the location of an independently positioned instrument on an image. In addition, the frame itself is a physical constraint during surgery.

The advent of accessible personal computers and affordable workstations provided the means to address some of these limitations. These processors enabled a variety of digitizing technologies to be brought into the operating room – technologies which could both define surgical coordinate space and locate points within that space. The computational ability of even the earliest personal computers could also perform the necessary calculations to co-register the surgical field and an imaging study. Lastly, these workstations could drive the graphics displays to make co-registered information useful to the surgeon. In accomplishing these three tasks of digitization within a coordinate space, co-registration of multiple coordinate spaces, and end-effector information, the operating room computer carried out all the tasks of the frame and itself became a stereotactic instrument.

The earliest prototype systems served primarily to demonstrate a concept, although from the onset the powerful utility of their guidance was appreciated. While numerous investigative groups developed systems of their own and a diversity of components and methodologies developed, the principles underlying the concept of frameless stereotaxy remained unchanged. Finally, the involvement of industry working in collaboration with early investigators brought refinement in the instrumentation and techniques, enabling widespread dissemination of the technology.

Specifics of Image-Guided Systems

Digitizers

Digitizers, whether mechanical or nonmechanical, are computerized systems that provide coordinate addresses for any accessible point within their working volumes. It is the means by which they accomplish this that distinguishes between the many types of digitizers.

Sonic Digitizers

When the Dartmouth program first explored types of digitizers that would free a stereotactic system from mechanical linkage to the surgical field, a decision was reached to implement a frameless system using a sonic digitizer. It was a well-established and affordable means to demonstrate a concept. Today, the cost and availability of other methods have made them competitive alternatives.

Acoustic range finders determine the distance between a microphone and a small spark gap that emits a broad-bandwidth click by measuring the time of flight of that acoustic impulse. Sensitive to air temperature, humidity and turbulence, this technique may appear difficult, but accuracies in the range of 0.15% over a 100-cm slant-range are realistic in commercially available systems, such as that of Science Accessories Corporation (Stratford, CT). Using an array of at least three microphones, the location of a spark gap in three-dimensional space can be uniquely determined. Through refinement of software algorithms and other modifications (such as a pilot calibration pole consisting of a spark gap and microphone separated by a known distance that thereby obviates the need to directly measure temperature), the accuracy of these systems can be further improved and made clinically useful. They do require line-of-sight between emitter and receivers.

Our first stereotactic operating microscope system used such a digitizer to track the position and orientation of a microscope to which an array of three spark gaps had been attached (2 – 7). Early prototypes worked with an array of three or four microphones initially on the ceiling and subsequently on an adjustable light track over the surgical field; eventually, the microphone array was attached to the operating room table itself. This last modification was greatly appreciated by the surgical staff, as it allowed the table to be moved without re-registration, a practice eventually incorporated into most frameless systems today, regardless of the digitizing technology employed.

Each time the microscope was moved, the spark gaps fired and the position was re-determined. The relationship of this new position to the imaging studies was then calculated and that information made available to the surgeon in a number of ways, as discussed later. While the earliest system obtained initial registration of the microscope and the surgical field by focusing the microscope on each of three scalp fiducial marks, this registration step was later facilitated by simply positioning a hand-held single spark gap at these fiducials sequentially.

Sonic digitizers have been incorporated into frameless systems by at least three other groups as well. Barnett, Kormos and colleagues (8 – 12) developed a “sonic digitizing wand” system using this technology interfaced initially to a Sun SparcStation I (Sun Microsystems, Mountain View, CA) and more recently to a more powerful Picker ViStar Medical Imaging Supercomputer (Picker International, Highland Heights, OH). Using hand-held instruments such as a bipolar cautery to which two spark gaps have been attached and a table-mounted microphone array, they have reported a mean linear error in localization of 66 targets in 22 patients of 3.1 mm ± 1.5 mm (SD), with 3 mm computer tomography (CT) slice thickness or 2 mm voxel magnetic resonance imaging (MRI) volume acquisition (11).

Reinhardt and colleagues (13 – 15) have independently developed a sonic-based system for the localization of hand-held instruments in the surgical field. In a later version of their system using a Science Accessories Corp. GP8-3D digitizer and an IBM-compatible personal computer, the microphones are placed on the instruments and the spark gap emitters on the distant array. They have reported digitizer accuracy in the laboratory of 0.897 mm ± 0.635 mm SD (15).

Bucholz and Smith (16) have reported an additional laboratory and preliminary clinical experience with a sonic digitizer. In the controlled, non-clinical setting, they achieved system performance similar to that of Reinhardt’s, although their system was less reliable in the nine operative cases reported.

Articulated Arms

Articulated mechanical arms allow localization within the surgical field through knowledge of the fixed length of each link and the angle at each joint. The latter can be measured by either potentiometers or optical encoders. With this information, it is possible to know the location of the tip of such an arm with respect to its base. After an initial registration step, the tip of the arm in the surgical field can be related to preoperative imaging studies. Watanabe and colleagues first reported this (17 – 21), and numerous other implementations, including those of Mosges and Schlondorff (22 – 24), Adams (25), Leggett (26), Guthrie (27 – 29), Maciunas (30 – 32), Goerss (33), Koivukangas (34), and Zinreich (35), have demonstrated the practicality of such a technique. The Mark II arm of the Vanderbilt group illustrates the kind of accuracy that can be achieved with an arm of this type. Measurement errors for known distances in the laboratory have been on the order of 0.14 mm ± 0.139 mm (SD); the average error in clinical use has been 2.35 mm ± 1.18 mm, and this subsequently has been improved even further (32). Such arms are without line-of-sight constraints, and are relatively easy to use and generally reliable in differing environments. They vary in size, weight and balance, but all involve the potential encumbrance of an additional mechanical instrument in the field.

Closely related to these passive, articulated localizing arms are robotic instruments in which actuators may actively drive the end effector to a selected point and orientation (Fig. 1). Investigations to date, including the pioneering work of Young (36) and Kwoh (37), Glauser and Fankhauser (38, 39), Drake (40 – 42), and Benabid (43), have demonstrated the feasibility of such an approach. Automated delivery of invasive instrumentation has not yet been widely embraced. Such acceptance awaits further development of the technology for reliability and safety. Robotic instrumentation may be used to position operating microscopes, as in the implementations of the SurgiScope (Elekta AB, Stockholm, Sweden) and the MKM (Zeiss, Oberkochen, Germany) systems, as well as that of Giorgi (44). An extension of this methodology to radiosurgery is under development at Stanford University, where a lightweight linear accelerator is being positioned by a robotic manipulator (45, 46).

Fig. 1. This ceiling-mounted robotic operating microscope holder (SurgiScope, Elekta AB, Stockholm, Sweden and DeeMed, Grenoble, France) is capable of both monitoring the position of the microscope's optical focal point and robotically positioning the microscope at a target selected on an imaging study.

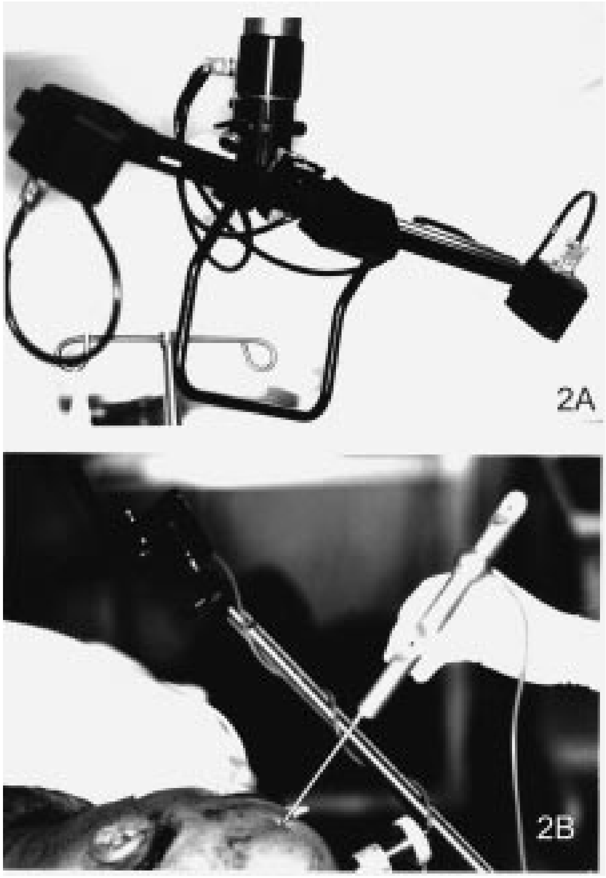

Fig. 2. **(A)** This optical digitizer by Pixsys, Inc. (Boulder, CO), consists of three cameras on an overhead bar that can track LEDs attached to any instrument in their field of view. LED arrays attached to hand-held instruments or to the operating microscope enable them to be tracked. **(B)** An LED array attached to the head clamp enables registration to be maintained when the operating table is moved.

Optical Digitizers

A variety of digitizing methodologies based upon optical imaging are currently in use. Both Pixsys, Inc. (Boulder, CO) and Northern Digital (Waterloo, Ontario, Canada) have developed digitizers based on multiple cameras fitted with linear charged-coupled devices (CCD) and cylindrical lenses that detect infrared light-emitting diodes (LEDs) or reflective devices within the surgical field (Fig. 2). As with sonic-based systems, there are line-of-sight constraints. However, systems developed by Stealth Technology (St. Louis, MO), Codman Corporation (Randolph, MA), BrainLab (Munich, Germany) and others have proven to be quick, reliable, and accurate. Multiple instruments, including the operating microscope, can be fitted with LEDs and easily tracked, as reported by Bucholz (16, 47), Zamorano (48), and Edwards (49). Theoretically, optical digitizers may be expected to be less sensitive than sonic digitizers to errors induced by the operating room environment, and this was demonstrated in one analysis (16); in practice, however, both achieve satisfactory accuracies. In another study, an optical digitizer compared favorably with a mechanical digitizer (50). It is important to note, however, that the largest contributions to overall system accuracy in the clinical setting have not been those of the particular digitizer, but those attributable to imaging resolution (i.e., slice thickness) and co-registration.

Ordinary video cameras can also be adapted for use as digitizers, as illustrated by the work of Heilbrun and colleagues (51, 52). Using two-dimensional images obtained from two different viewing angles, the three-dimensional locations of markers seen in both images can be determined. The University of Utah group has shown application accuracy comparable to that of the BRW frame (Radionics, Burlington, MA) (52).

At Dartmouth we have used a similar technique, employing high resolution (1524 by 1012 pixel CCD) Kodak DCS 200 digital cameras (Kodak, Rochester, NY) attached to the operating room ceiling on pan-tilt mounts. Interestingly, the algorithms used by such a technique are analogous to those employed by classical stereotaxy performed with intraoperative orthogonal radiographs.

Electromagnetic Field Detectors

Systems based upon a transmitter that generates an electromagnetic field, and a receiver that can be localized and oriented in three-dimensions based upon its detection of that field, offer yet another method of guidance. Since ferro-magnetic material within the operating room environment can distort the electromagnetic field, older systems — such as the Polhemus (Colchester, VT) — have generally not been well suited to surgery. A newer system based upon a pulsed DC field, and consequently less susceptible to environmental materials (Ascension Technology Corporation, Burlington, VT), is being adapted for intraoperative stereotactic purposes (Fig. 3). Manwaring (53) has described its implementation in tracking an endoscope, and we have used it for tracking an intraoperative ultrasound transducer. Kato (54) and Goerss (55) have each described adaptations such as a probe localization system, similar in function to the articulated arms in use. The method is without line-of-sight constraints and interferes minimally with the surgical field; an average error of less than 3 mm is being reported (55).

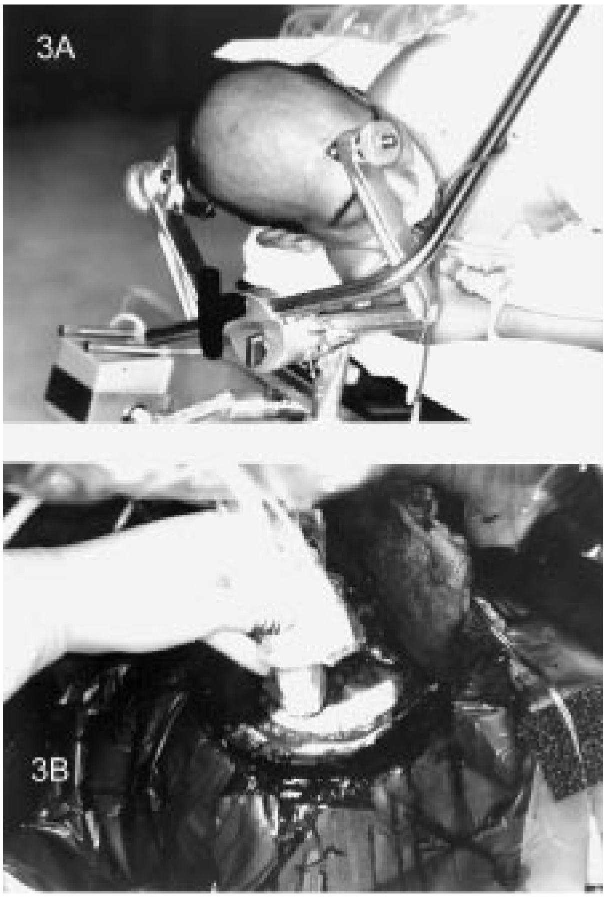

Fig. 3. **(A)** The transmitter of an electromagnetic field-sensing digitizer (The Bird, Ascension Technology Corporation, Burlington, VT) is located near the attachment of the head clamp to the table. **(B)** A small detector, here attached to an ultrasound probe, can be localized through its sensing of the electromagnetic field generated by the transmitter.

Co-registration

Independent of the type of digitizer used, all stereotactic systems require determination of the relationship between at least two different coordinate spaces. The simplest method of determining this relationship is that based upon knowing the locations in both spaces of at least three non-collinear points. This method has been used by most frameless systems and utilizes either fiducial markers placed on the patient’s scalp at the time of imaging or natural landmarks, such as the nasion, lateral canthus, or tragus (3, 4, 17, 56, 57). The locations of these points on the CT or MRI scan are recorded, and at the start of the operative procedure, a digitizer is used to locate these same points in operating room space (Fig. 2B). Well-established algorithms enable one to then derive the matrix transformation or equivalent (such as direction cosines), with which one can move between the two coordinate spaces readily.

Use of natural landmarks has generally been slightly less accurate than fiducial marker techniques (which with special efforts can be made extremely accurate [58]), in large part because the former relies on usually less discretely defined points. In the recent experience reported by Golfinos (59), anatomic landmark and surface-fit algorithms achieved an accuracy approximately one-half of that accomplished using fiducial-based registration. Satisfactory degrees of accuracy can be achieved, however, and there are potential advantages to the former strategy. If the requirement for prospectively placed fiducial markers is eliminated, it becomes possible to co-register imaging studies obtained prior to the intent to operate.

Methods other than those matching sets of ordered points can also determine the relationship between one coordinate space and another. Initially for the purpose of co-registering different imaging studies with one another, Pelizzari and Chen (60) described a non-fiducial technique by which the surface contour of the head from one study could be fitted to the analogous contour from another study, much as a hat fitting a head. Others have developed similar mathematical techniques for matching surfaces, such as that used by the Analyze image processing program (The Mayo Foundation, Rochester, MN) (61). Alternatively, the curvatures inherent in the surface of a head, rather than the collection of actual points that represent the surface, may themselves be used to accomplish this matching task, as demonstrated by Friets (5). With the use of digitizing technologies such as those described earlier, surface-matching strategies can be adapted to operative planning (62) or to surgery itself. Such a registration method, of course, can be used in combination with a fiducial-based algorithm to optimize the step even further, as is possible with the ISG Viewing Wand (ISG Technologies, Mississauga, Ontario, Canada) (63). This ability to match surfaces or contours can be used with any number of digitizing modalities, including articulated arms, sonic digitizers, optical systems, and electromagnetic sensors. All that is required is digitization of a sufficient portion of the surface to enable reliable matching with the surface derived from preoperative imaging data.

From an efficiency perspective, the strategy of employing non-contact digitizers, which can collect necessary data in a more automated fashion, has great appeal. Video camera and electronic camera systems, such as those developed by Heilbrun et al. (52), at Dartmouth, and by Gleason et al. (64), have demonstrated the ability to capture sufficient contour and surface feature data to permit co-registration with MRI or CT studies. Laser range finders may be used similarly for this purpose. The sophistication of co-registration strategies and algorithms is evolving rapidly (65), and the accuracy, time efficiency and degree of automation are constantly improving.

Stereotactic Display and Effectors

Having accomplished co-registration of image and surgical coordinate spaces, stereotactic systems must then make the derived information available to the surgeon in a useful manner. Our operating microscope accomplishes this with a small monitor attached to the microscope through a beam-splitting assembly (3, 5); Kelly has developed a similar interface (66). The resultant heads-up display enables the surgeon to see both the conventional surgical field and the superimposed, computer-generated graphics. The default option in our system displays the intersection of the focal plane of the microscope and any object of interest, such as a tumor, so that the segmented structure is depicted in the correct location, orientation and scale. Alternatively, any other parallel plane may be superimposed, an often-used option in getting to a lesion. Should the targeted object be out of the field of view, the system can display a graduated line connecting the focal point (in the center of view) and the projection of the center of gravity of a deeper object into the focal plane. Wall monitors display appropriate CT or MRI images in which the microscope's focal point is represented by a cursor.

Those frameless stereotactic systems that track hand-held pointers or instruments provide feedback to the surgeon with similar external monitor graphics. Multiplanar displays showing annotated axial, coronal, sagittal and reformatted "down the trajectory" planes as well as three-dimensional renderings, with and without cutaway views, all provide easily used assistance (Fig. 4). Displays of planes perpendicular to the optical axis of the operating microscope or the long axis of an instrument, and accompanying views parallel to that axis in several planes, can be useful in understanding what lies along a specific trajectory. Comprehension of such data, however, is sometimes difficult and non-intuitive in unorthodox, oblique planes. The ability of a display to provide the surgeon a choice among options based upon both the patient's and the tool's coordinate systems is highly desirable.

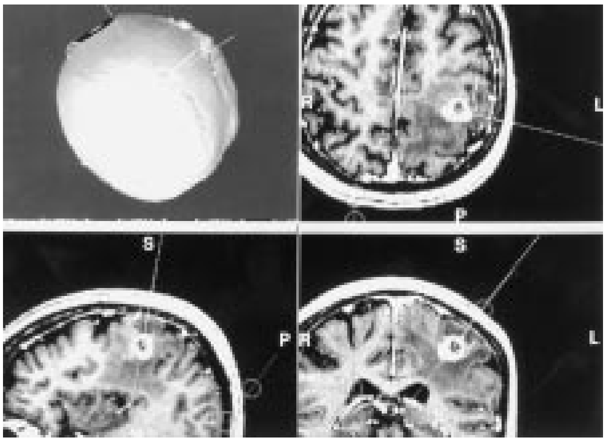

Fig. 4. (Top left) Reconstructed skull for planning burr holes. (Top right) Axial view of left (L) parietal (P) tumor. (Lower left) Suggested route (S) in sagittal view of parietal (P) lesion. (Lower right) Suggested route (S) in coronal view of enhancing left (L) tumor.

Clinical Applications

While feasibility and accuracy assessment have been appropriate goals of early work, clinical experience with frameless stereotactic systems has been growing. Practical intraoperative utility has been favorable in early reports, and useful applications across a wide spectrum of procedures are being described (10, 12, 59, 67). Access to the structural lesion, defining the extent of the resection and thereby assuring completeness of intended surgery, and protecting non-pathologic critical structures are all useful and accepted principles in any surgery. These principles are of central importance to those oriented toward minimally invasive surgery, and each is more attainable through the techniques of surgical navigation. Below is an examination of the techniques described above, in their application to a variety of clinical settings.

Intracranial Neoplasms

Surgery for the resection of subcortical and deep tumors has perhaps been the most common application of frameless navigation (10, 12, 14, 35, 40, 56, 66, 68, 69). This application extends common stereotactic localizing capabilities to open craniotomy, and a variety of benefits are derived. Preoperatively, precise determination of the location of the tumor and planning of a trajectory to approach the lesion are carried out on a graphics workstation. Once co-registration has been performed in the operating room, stereotactic guidance can direct the location and extent of craniotomy. The location, shape, and size of the skin incision and bone flap can be tailored to minimize the overall exposure.

Surface features of the cortex can be predicted, allowing vascular structures to be avoided and even excluded from the opening. Once exposure of the cortical surface is complete, navigational systems can direct the surgeon to the optimal cortical incision along the predetermined trajectory, by means of the graphics display or, in some systems, following lasers illuminating the trajectory to the focal point. Progress toward the lesion can be monitored dynamically on the computerized imaging studies.

Upon arrival at the lesion, the resection can be guided by these same techniques. A navigation system can track the location of a surgical instrument and map the instrument's location to the imaging studies, or alternatively, the position of the microscope itself can be tracked, allowing for localization of the focal point. Using this technique, the visual field is directly mapped to the imaging study. With either method, progress through the resection can be monitored and non-pathologic structures avoided. For both assessment of complete resection and avoidance of normal tissue, the surgeon's accuracy and efficiency are enhanced.

Vascular Malformations

Vascular applications with reasonably well understood anatomic relationships, such as aneurysm clipping, might be expected to gain less from stereotactic guidance. Derived benefits may be less apparent for surgery in the extra-axial spaces where normal landmarks may be available to assist orientation. Nevertheless, these interventions may benefit from recent advances in computer visualization of the pathology (70).

Vascular malformations, on the other hand, represent less-stereotypical pathology. Arteriovenous malformations (AVMs), with their individualized feeding and draining vessels, are associated with a sustained risk of hemorrhage. Cavernous malformations, though their natural history is less well understood, can also present a challenge when symptomatic, because of their location. Vascular malformations may lie in close proximity to eloquent areas of cortex or deeply, where access to the lesion may necessitate traversing functional neurologic tissue. Surgery in either of these locations carries risk of neurologic deficit, but is often the management of choice. Surgical navigation can play a role in decreasing this surgical morbidity. Several reports have demonstrated the efficacy of these techniques on such lesions (14, 70 – 75).

In the case of the surface AVM near eloquent regions such as speech or motor centers, the incorporation of functional imaging data can enhance the ability of the surgeon to avoid these critical regions. Functional imaging such as positron-emission tomography (PET) scanning or functional MRI can be co-registered with other imaging data, as well as the patient. Another technique integrates image guidance with intraoperative functional mapping. The bipolar stimulator used to determine motor, sensory, and language areas during mapping can be localized on the imaging studies, and an integrated database developed. Preoperative planning may also help with the identification of vascular structures on the cortical surface, and recognition of these landmarks intraoperatively can give the surgeon additional confidence. With deep-seated AVMs, target trajectory techniques, as described for subcortical tumors, are useful in guiding the surgeon to the lesion with minimal disruption to surrounding normal brain. With an accurate trajectory, the opening as well as the surgical corridor can be kept to minimal size.

Epilepsy

Open functional surgery in general, and surgery for epilepsy specifically, are particularly well suited to computer-assisted, stereotactic techniques. The identification of a seizure focus and its excision with preservation of normal function often requires the surgeon to remove tissue that is visually indistinguishable from normal brain. This may at times be the surgical equivalent of "flying blind." Therefore, the integration of multiple imaging modalities and electrophysiologic data into a navigational system can be more helpful than in any other surgical procedure.

Surgical navigation techniques can be used in both the evaluation and the treatment of patients with medically intractable epilepsy (67, 76–79). For patients whose seizure focus is difficult to localize, the co-registration of preoperative imaging such as high-resolution MRI and physiologic studies such as PET, ictal single photon emission computed tomography (SPECT), and functional MRI can help with the planning and accurate placement of invasive recording electrodes.

In those patients in whom the seizure focus has been accurately mapped to the cerebral cortex by invasive monitoring, additional steps can be taken to assure the accuracy of resection. A postoperative CT scan with the electrodes in place, routinely obtained and co-registered with the previous database for that patient, enables the navigation system to identify the contacts that overlie the seizure focus intraoperatively. All of this can be tailored to the individual patient, a feature critically important in neocortical epilepsy.

In cases where epilepsy is thought to be secondary to a lesion, the trajectory planning features of the surgical navigation system direct the surgeon to that lesion with equal accuracy, as described above for subcortical tumors or deep-seated vascular malformations. Selective amygdalohippocampectomy is similarly benefited. This procedure can be accomplished through an enlarged burr hole and can replace a temporal lobectomy in selected cases.

The Spine

The greatest challenge for frameless applications in the spine has been in co-registration. The inability to fix external fiducials and the non-rigid relationship between multiple spinal segments reliably or easily has precluded methodologies used for cranial procedures (7). Co-registration for the spine is most easily done through exposed bony structures during surgery, with registration of each segment performed independently. These landmarks can be seen clearly on preoperative imaging studies and, once exposed, work well for co-registration purposes.

The goal of surgical navigation in the spine, as in intracranial work, is the localization and orientation of structures not visible in the surgical field. Although localization of tumors and fracture fragments in the spine can be done, the predominant application in spinal surgery has been in assisting placement of pedicle screws. This procedure has traditionally been done with the guidance of intraoperative radiographs or fluoroscopy, but these additional studies can be time consuming and inadequate for accurate placement. Surgical navigation takes advantage of the preoperative imaging and offers the additional benefit of three-dimensional visualization. After bony exposure and registration, a tracked probe or drill guide is adjusted until aligned with an optimal trajectory. Coupled with depth estimates, the final location of the screw can thus be predicted (80–82).

Endoscopy

Rigid endoscopy lends itself well to frameless stereotaxy, since orientation of the often restricted visual image can be facilitated by integration with standard radiologic studies (53, 83). Flexible endoscopes are obviously more problematic. However, this type of guidance can be helpful in terms of performing tumor biopsies or third ventriculostomies. The information available through the navigation system adds an additional degree of confidence concerning actual location. Another example that has been described is that of fenestration of loculated hydrocephalus. This is a challenging disorder for endoscopic treatment because, though the endoscope is less invasive, the potential for disorientation is high. If the navigation system can help in the preoperative planning of a single trajectory that will encounter all of the cysts and enable them to be fenestrated sequentially, the concerns for disorientation and incomplete treatment can be greatly reduced. Interestingly, the intraoperative utility of the navigation system is reduced in this situation because of the significant amount of movement of intracranial tissue during this procedure, with resultant loss of initial co-registration. Nevertheless, the preoperative planning may have already improved the potential outcome.

Future Directions

Current advances in frameless stereotaxy include improvement in the efficiency and accuracy of registration (84), strategies to cope with intraoperative brain displacement and deformation ("shift") (85), and refinement of information display systems (86, 87). Those settings in which structures within the surgical field may have deformed or shifted in relation to the original registration features are not accounted for by the above co-registration methodologies. The error arising from such movement may be accounted for through re-imaging, re-registration, or both. Digitization of the same or different registration points (either by the same digitizing technology or through the use of different intraoperative imaging devices, including cameras, ultrasound, or even CT and MRI scanning) is being investigated. Through interpolation or predictive modeling techniques, less resolved (and consequently less expensive or constraining) imaging modalities may be satisfactory for this purpose.

A variety of workstation applications, as well as viewers, goggles and helmets developed for virtual reality or augmented reality (in which real perception is also preserved, as in a microscope's heads-up display) applications, are also becoming available. Sophisticated graphics, with three-dimensional renderings, appropriate segmentation, variable transparencies, fused imaging modalities, and manipulable scale and perspective can assist structural understanding and surgical planning considerably. Simulation of the surgeon's intraoperative perspective during actual surgery, as implemented by the Brigham group (63), functions as a navigational guide in itself.

Conclusion

The power of frameless stereotaxy has already evolved to a point where its use enables the surgeon to be minimally invasive. Improved planning leads to smaller incisions. Improved navigation helps prevent injury to local structures. Improved target localization ensures confidence in the completeness of a surgical resection. All of these can improve the quality of care, decrease operative time, and lower expenses.

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