Intraoperative Imaging:
Evolutions, Options, and Practical Applications

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"Stereotactic procedures involve two frightened people separated by a needle."—Attributed to Robert Selker, M.D.

Image guidance is being increasingly used for brain operations in today's era. This includes craniotomy for most nontrauma indications, conventional stereotactic surgery, functional surgery, and radiosurgery.[27] The personal interest of the senior author (LDL) in this field began at the time that he started his residency in 1975. The first computed tomography (CT) scanner, an Electric & Musical Industries (EMI) device with a water bag, arrived on July 1, 1975, his first day as a resident. This scanner required the use of a water-filled tank with a preshaped rubber "head cap" at the front, which enclosed the patient's head. This tank was used to reduce the dynamic range of the radiation reaching the detectors. This first CT scanner was developed by Hounsfield in his laboratory at EMI and took several hours to acquire the raw data for a single scan or "slice" and took days to reconstruct a single image from these raw data. The recognition of the value of computer-based imaging became immediately apparent.[39] During the subsequent years of training, the senior author had an opportunity to work with an innovative neuroradiologist, Arthur Rosenbaum, M.D., and an engineer, John Perry, Ph.D., who then headed the imaging division of Pfizer Medical Instruments. Together, we developed an image-guided stereotactic system using the now well-known N-localizer technology. This elegant solution was proposed by Perry et al.[41] and Rosenbaum et al.[44] independently and virtually simultaneously as publications from Brown[2] and Roberts and Brown[43] of Utah. The adaption of CT for stereotaxic operations required the transformation of the coordinates of the target point from the CT image space into the stereotaxic frame space. On each slice, the XY coordinates of the nine points representing the slices of the edges and diagonals of the localizer define the plane of the slice with regard to the plane of the head ring.

During the interval of 1979 to 1980, 13 stereotactic procedures were performed in a diagnostic scanner at our hospital. An opportunity presented itself for the senior author to undergo additional training focused in stereotactic and functional neurosurgery at the Karolinska Institute. Under the auspices of the American Association of Neurological Surgeons Van Wagenen Fellowship, the senior author spent one year in Stockholm studying under the tutelage of Professors Erik-Olof Backlund and Lars Leksell. During this interval, the newly redesigned Leksell CT-compatible stereotactic head frame[20] was used for dedicated brain biopsies under the direction of its inventor, Lars Leksell (*Fig. 9.1*). This fellowship included experience with stereotactic surgery, gamma knife radiosurgery, and functional surgery.

On returning to Pittsburgh in 1981, the senior author began a quest to obtain a dedicated CT scanner-equipped operating room at a time when the regional health systems agency had allocated two diagnostic CT scanners to the entire city of Pittsburgh. After a number of meetings, we obtained a certificate of need to install a dedicated GE 8800 scanner (General Electric, Fairfield, CT) specifically for therapeutic neurosurgical purposes (*Fig. 9.2*). We built a new operating room and began our first series of stereotactic procedures.[3,6,19,21,28,29,31,33,35,37] The scanner was updated to a GE 9800 in 1991.

Stereotactic and functional neurosurgery had gone through a period of relative inactivity during the 1960s and 1970s at most U.S. centers because of the development of more effective antiparkinsonian medications. This fact also led to a decline in the training of neurosurgeons who could perform functional neurosurgery. Part two of our plan for developing image-guided neurosurgery was the introduction of the Leksell gamma knife into the U.S.[30] Intense planning for this project began in 1982. After involving the dedication and talents of many people, we were able to introduce this groundbreaking technology into North America. The first 201 source cobalt-60 gamma knife was installed at the University of Pittsburgh, Presbyterian–University Hospital, and the first patient was treated in August 1987.[25,26,30] By August 2008, 9300 patients had undergone gamma knife radiosurgery at our center.

There are a number of basic tenets necessary to introduce new technologies into the neurosurgical mainstream. The first principle is that the technology should be simple and practical. It must assist the surgeon to perform the operation,

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FIGURE 9.1. Professor Lars Leksell watches the senior author performed a stereotactic biopsy procedure in the CT scanner at the Karolinska Sjukhuset in 1980. George Norén, M.D., Ph.D., is in the background.

FIGURE 9.2. The first dedicated therapeutic CT scanner for brain surgery was installed at the University of Pittsburgh Medical Center in 1982. The room had a dedicated GE 8800 CT scanner and a Phillips C-Arm image intensifier.

it should be efficient, it must promote better outcomes, and it must reduce morbidity. Intraoperative imaging using CT and later magnetic resonance imaging (MRI) technologies fulfilled the goals. In the sections to follow, we present examples that define the value of high-resolution neurodiagnostic imaging during neurosurgery procedures.

Frame-Based Stereotactic Surgery

Our experience from 1977 to 2007 using frame-based stereotactic surgery is shown in *Table 9.1*. Many procedures initially used CT imaging for stereotactic surgery. We added MRI-based target localization in selected cases beginning in 1991.[23,32] As the resolution of MRI scan imaging improved, we increasingly relied on MRI for functional neurosurgery in patients eligible for MRI.[23] We also used MRI for selected biopsies, especially those in high-risk locations or when (*Fig. 9.3*) their imaging characteristics were best defined by MRI.[15,32] All of our patients undergo stereotactic frame placement in an operating room environment followed by imaging either in our dedicated CT operating room or a nearby diagnostic 1.5-Tesla

TABLE 9.1. Stereotactic brain surgery, University of Pittsburgh Medical Center–Presbyterian, 1979 to 2007

	No. of Patients
Diagnostic biopsy	1664
Cyst aspiration	197
Radiation implant	145
Brain abscess	97
Catheter and cyst reservoir insertion	19
Hematoma aspiration	9
Frame-based craniotomy	10
Ventriculostomy placement	6
Total	2147

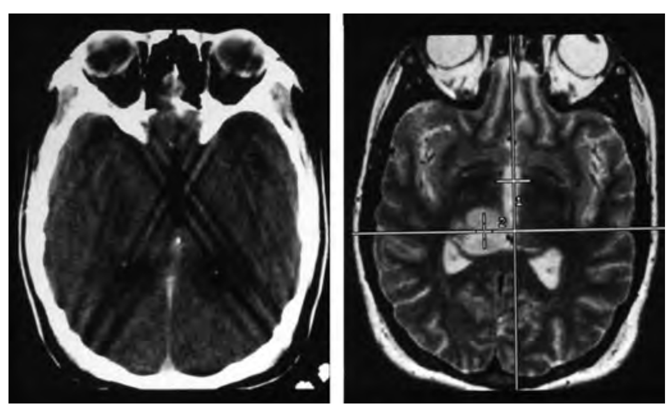

FIGURE 9.3. Frames provide precision and reliability. Certain lesions are best seen with MRI. CT imaging (left) showed poor contrast enhancement and pin artifacts compared with enhanced MRI (right) for this thalamic glioblastoma.

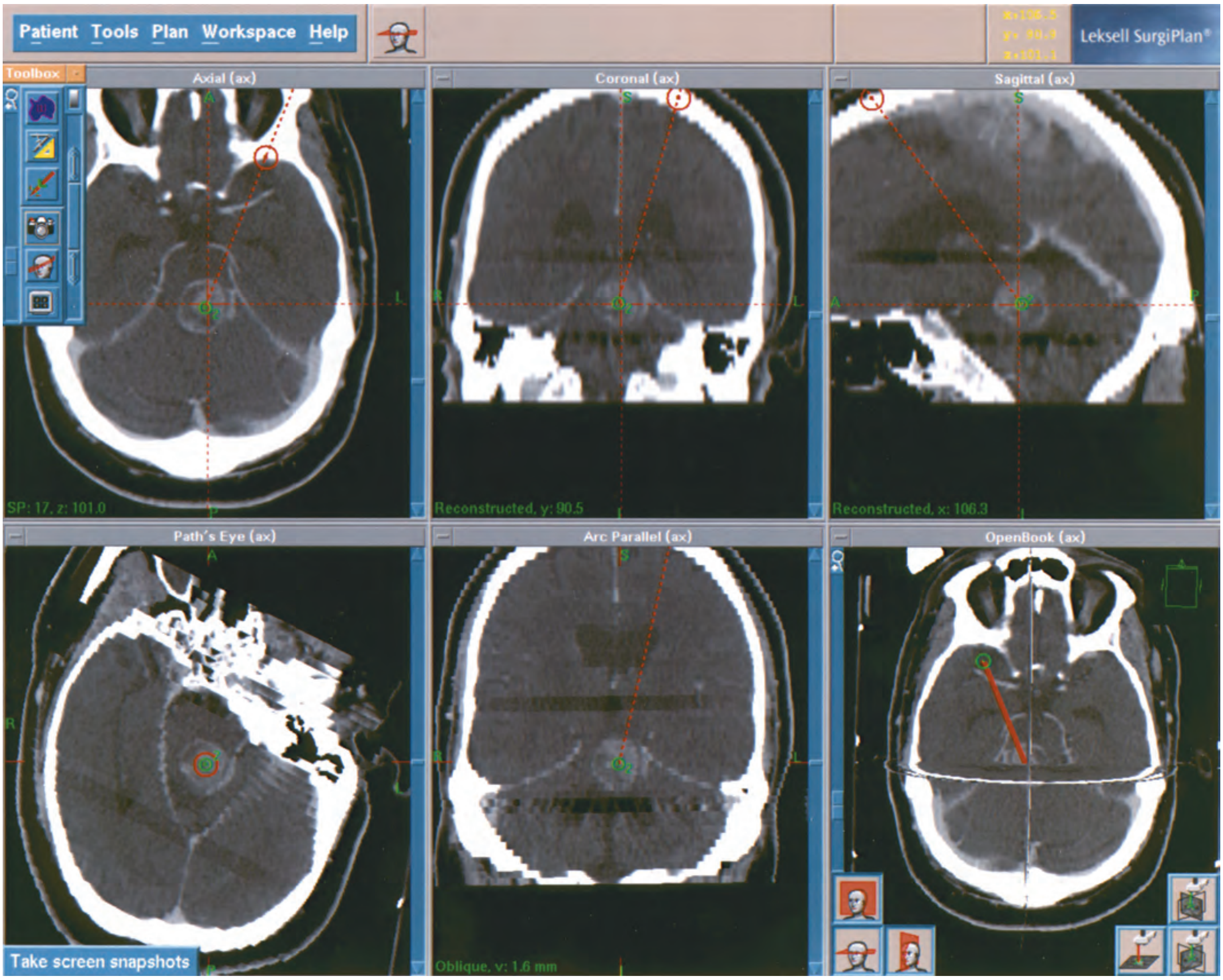

FIGURE 9.4. Computer surgical planning systems facilitate preplotting of probe trajectories, which are then precisely reproduced using the stereotactic arc.

MRI unit. Calculation of coordinates is performed either using the standard software available on the scanners or, more recently, using an image integrated surgical planning system (SPS; Elekta, Inc., Norcross, GA). We precisely preplot probe trajectories to reach the target and choose the route designed to avoid as many pial or ependymal surfaces as possible (*Fig. 9.4*).

In those cases in which diagnostic questions are posed, we perform stereotactic biopsy only after a thorough patient workup fails to reveal a clear diagnosis. In our experience, the likelihood of a positive histopathological diagnosis is inversely related to the length of the preoperative differential diagnosis. If a patient has a contrast-enhancing mass lesion, in which the differential diagnosis is primarily glioblastoma, lymphoma, metastasis, or brain abscess, then an answer will be achieved in virtually 99% of patients. However, for more complex cases in which the differential diagnosis may include degenerative disorders, inflammatory disorders, infectious etiologies, demyelinating processes, and vascular events, the likelihood of a positive diagnosis by brain biopsy lessens. In general, the highest likelihood of a positive biopsy occurs when the sample comes from the contrast-enhancing portion of the lesion (if such exists). Brain biopsies are performed in all areas of the brain, including the basal ganglia, pons, and medulla (*Fig. 9.5*). Many lesions in the deep locations of the brain can be approached from a single transfrontal intra-axial trajectory. In selected cases for lesions adjacent to the fourth ventricle or cerebellar hemisphere, a transcerebellar trajectory is performed with the patient moved to a semi-sitting position on the operating room table. In virtually all cases in patients older than 12 years, the procedures are performed under monitor-assisted conscious sedation.

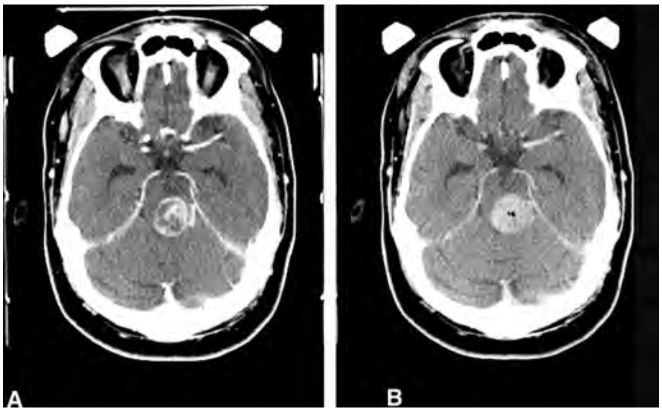

FIGURE 9.5. Medullary biopsy of this patient with a suspected central nervous system lymphoma is done by a transparenchymal approach starting at the coronal suture. Air density at the target site verifies the biopsy site using intraoperative CT.

The risks of bleeding from a stereotactic approach are elevated in the presence of an unrecognized coagulopathy, the use of aspirin or clopidogrel, or poor trajectory planning.[8] We make sure that patients have a normal coagulation profile and are off aspirin for 1 week and clopidogrel for 2 weeks before consideration of diagnostic brain biopsy. Within the last 15 years, all frame-based biopsy procedures have been done with a twist drill craniotomy approach.[5,6,18,36] The open burr hole technique was abandoned more than 15 years ago. Since that time, the risk of an entry site infection has declined to virtually zero. Hospital stays are 24 hours or less. Although "frameless" biopsy has increased in popularity, we think that the concept of general anesthesia, three-point (Mayfield) rather than four-point fixation, frequent use of a burr hole, and other often more complex tools to hold probe seems counterintuitive.

An experienced neuropathological team is critical. Reaching a final diagnosis involves a collaborative effort with the neuropathological team, including review of the pre- and postoperative images. It is often wise to review your clinical suspicions with the neuropathologist to "set the mood." A collegial and collaborative interaction followed by a multiplicity of immunoperoxidase and genetic studies will greatly increase accuracy. A confirmatory intraoperative CT scan is always done, which shows small air density at the target site. This image is used to demonstrate to the neuropathologist that we are completely "on target."

In our experience, the current risk of a brain biopsy hemorrhage requiring evacuation using frame-based techniques is less than 0.5%[8] (*Tables 9.2* and *9.3*). Frame-based systems provide extreme accuracy to less than 1 mm and rigid probe fixation is critical. In addition, we are able to precisely reduplicate the pathway of the needle previously plotted using the surgical planning system. Dealing with bleeding requires some fortitude in the rare events when it occurs. A needle is left in position, and the stylet is advanced periodically into the needle to make sure that thrombus does not prevent exit of blood.

TABLE 9.2. Complications of frame-based stereotactic procedures, University of Pittsburgh Medical Center–Presbyterian, 1981 to 2007

Procedure Type	Total	Hemorrhage[a]	Seizure	Superficial Infection[b]	Other[c]	Total Complications
Diagnostic biopsy	1664	43 (2.58%)	6 (0.36%)	2 (0.12%)	20 (1.2%)	71 (4.2%)
Cyst aspiration	197	5 (2.53%)	3 (1.52%)	2 (1.01%)	5 (2.53%)	15 (7.6%)
Radiation implant	145	2 (1.37%)	1 (0.68%)	1 (0.68%)	6 (4.13%)	10 (6.9%)
Brain abscess	97	1 (1.03%)	—	4 (4.12%)	5 (5.15%)	10 (10.3%)
Catheter and cyst reservoir insertion	19	—	—	—	1 (5.26%)	1 (5.2%)
Hematoma aspiration	9	—	—	—	—	—
Frame-based craniotomy	10	—	—	—	—	—
Ventriculostomy placement	6	—	—	—	—	—
Pallidotomy	147	2 (1.36%)	—	—	2 (1.36%)	4 (2.7%)
Thalamotomy	72	1 (1.38%)	1 (1.38%)	—	5 (6.94%)	7 (9.7%)
Deep brain stimulation (movement disorders)	98	1 (1%)	—	1 (1.02%)	3 (3.06%)	5 (5.1%)
Depth electrodes for seizures	95	1 (1%)	—	1 (1.05%)	—	1 (1.2%)
Deep brain stimulation (chronic pain)	24	—	—	—	1 (4.1%)	1 (4.1%)
Cell transplantation	20	—	—	—	—	—
Mesencephalotomy/capsulotomy	4	—	—	—	—	—
Total	2607	56 (2.15%)	11 (0.42%)	11 (0.42%)	48 (1.84%)	125 (4.79%)

[a]Six (0.2%) patients required craniotomy and hematoma evacuation.
[b]Includes cerebritis and meningitis.
[c]Includes deep vein thrombosis, cardiac arrhythmia, pneumonia, anesthesia-related complications, urinary tract infection, and deep wound infection.

TABLE 9.3. Management of brain hemorrhage after 2607 frame-based stereotactic procedure, University of Pittsburgh Medical Center–Presbyterian, 1979 to 2007

	No. of Patients	Percent
Observation	40	72.7
Insertion of EVD	6	10.9
Craniotomy and evacuation	6	10.9
Burr hole aspiration	3	5.5
Total	55	100

EVD, external ventricular drain.

TABLE 9.4. Stereotactic management of brain cysts, University of Pittsburgh Medical Center–Presbyterian, 1981 to 2007

	No. of Patients
Tumor cyst aspiration	119
Colloid cyst aspiration	47
Craniopharyngioma cyst aspiration	31
Total	197

Nothing is injected into the needle. With time, bleeding stops. Although routine postoperative imaging will show a small hemorrhagic density after such events, their clinical incidence is usually insignificant. As shown in *Table 9.2*, 0.2% required a reoperation to evacuate a hemorrhage secondary to the stereotaxic procedure.

Brain Cyst Management

Table 9.4 shows our experience with stereotactic cyst aspirations. The alleviation of brain cysts by simple aspiration has been done in a large variety of patients, including those with glial cysts, neuroepithelial cysts, and in the management of cystic craniopharyngioma.[5,13,40,42] Simple aspiration of craniopharyngioma cysts may be periodically needed, and we prefer this as opposed to placement of an Ommaya reservoirs drainage system (*Fig. 9.6*). Using the fine-needle (0.9-mm) puncture technique advocated by Backlund, we are able to introduce colloidal chromic phosphate radioisotope P^{32} into a craniopharyngioma to result in involution of the cyst over the course of time.[42] Cyst reservoir systems, in our experience, seem to irritate a craniopharyngioma leading to a progressively more frequent need for cyst aspiration. In contrast, a P^{32} injection with a dose of approximately 20,000 cGy offers an effective management for primarily monocystic craniopharyngiomas greater than 5 mL in volume. Because it is a pure beta emitter, the falloff of dose is quite rapid, thereby sparing dose to surrounding critical structures such as the optic apparatus. *Table 9.5* shows our experience with the stereotactic isotope strategies.

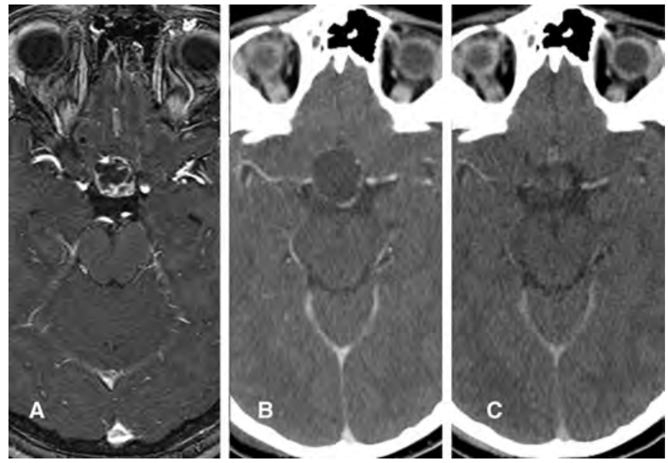

FIGURE 9.6. Axial contrast-enhanced MRI of a 13-year-old with declining vision showing craniopharyngioma at the time of radiosurgery (*A*). However, 1 year later, a cyst enlarged (*B*). The cyst was evacuated by transfrontal stereotactic aspiration (*C*).

TABLE 9.5. Stereotactic radiation procedures, University of Pittsburgh Medical Center–Presbyterian, 1981 to 2007

	No. of Patients
Intracavitary radiation (P^{32})	
Craniopharyngioma	73
Glioma	13
Arachnoid cyst	4
Subtotal	90
Stereotactic interstitial radiation (I-125 brachytherapy)	
Glioma	51
Ependymoma	2
Malignant meningioma	1
Central nervous system lymphoma	1
Subtotal	55
Total	145

Image-Guided Craniotomy

Frame-based image-guided craniotomies have been performed for more than 25 years. In the early 1980s, we began to perform image-guided resections using the Leksell frame in our intraoperative CT suite. Our initial experience failed to disclose significant benefit from intraoperative CT-assisted cytoreductive glioma surgery.[4,7,18,38] We found little evidence that taking out the "majority" of a glial tumor yielded superior results. It is possible that patients eligible for extensive cytoreductive surgery, primarily those with lobar or polar tumors, may benefit from such an approach if their tumors have less infiltrative borders and are located in less critical regions of the brain. Such surgery must then be combined with additional adjuvant management strategies, including radiation therapy, in certain cases chemotherapy, and potentially radiosurgery. Although we are confident that centers using intraoperative MRI are making headway in terms of their ability to better resect glial neoplasms, we are, nonetheless, struck by the fact that in a 30- to 60-g glial tumor that may have 3 to 6 $\times$ 10^{10} cells, after a 99% ("gross total") removal, it now contains 3 to 6 $\times$ 10^{8} cells.[45] Although it is possible that subsequent adjuvant management may be better able to control such tumors, to date, there is little proof of this concept. To define such a benefit, a large prospective, randomized trial would be needed to demonstrate a significant increase in survival in Grade II, Grade III, or Grade IV gliomas after aggressive resection.[34]

The fact is that most patients with glioma do not have focal lobar tumors, which makes them eligible for extensive cytoreductive surgery. For those that do, aggressive surgery may be desirable. Surgery alone is rarely curative of such tumors. Over the last 5 years, we have come to suspect that prior outcomes studies related to Grade 2 fibrillary astrocytoma are unreliable. Many, if not most, patients included in these prior studies would be found to have 1p19q-deleted tumors (oligodendrogliomas) rather than astrocytomas. Patients with oligodendroglioma have a better prognosis and often have tumors with less infiltrative borders, thereby enhancing the opportunity for better cytoreductive surgery. The diagnosis and management of many glial tumors seem to be moving targets.

Abscess Management

We have performed stereotactic aspiration for the diagnosis and simple or catheter assisted drainage of 97 patients with brain abscesses. Frame-based stereotactic surgery is an excellent way to manage brain abscesses.[22,24,42] Like in all surgical pyogenic infections, the principles include early recognition, drainage, and identification of the appropriate organism when possible. Brain abscesses adjacent to the ventricular system and associated with extensive mass effect are true surgical emergencies. A variety of techniques are available to manage brain abscesses, including frame-based and frameless approaches. We have treated most brain abscesses using a twist drill craniotomy, stereotactic puncture, followed by drainage of the abscess cavity. The bacteriological studies in most cases are able to define the causative organism(s). At the time of drainage, appropriate broad-spectrum antibiotics are given in the operating room. We perform a full assessment of the potential sources for a pyogenic brain abscess, including heart, sinus, or other septicemia sources.

Rarely do brain abscess cases require redrainage of the abscess when it is not progressing as expected. The treatment regimen consists of appropriate antibiotic management, placement of a catheter in the abscess (for volumes estimated >5 mL), and gradual removal of the drainage catheter after several days. This approach has a high success rate and virtual elimination of mortality from bacteriological brain abscesses. For patients with fungal abscesses in the context of chronic immune suppression, especially those in the transplant arena, biopsy and identification of the organism allows the potential for aggressive antifungal management. In our community, the need for brain biopsy in the diagnosis of HIV-related conditions has declined. Patients with a progressive mass lesion within the brain in the context of AIDS normally undergo empiric antitoxoplasmosis treatment first. Biopsy is performed if the lesion progresses. A positron emission tomography or single photon emission CT can be used to confirm that a lesion is hypermetabolic as one would expect if the lesion were a brain tumor. A lesion that is hypermetabolic on the positron emission tomography scan and cerebrospinal fluid test positive for Epstein-Barr virus can reduce the need for a brain biopsy in a patient with AIDS. The success of highly active antiretroviral therapy has also resulted in a reduction in new cases of primary central nervous system lymphoma. On occasion, however, a brain biopsy is often required for central nervous system lymphoma not only to make the histological diagnosis, but also for the ability to provide prognostic information to family members and patients who may have progressive multifocal leukoencephalopathy associated with AIDS.

Functional Neurosurgery

Functional neurosurgery is dependent on high-resolution multiplanar imaging. In the 1980s, when deep brain stimulation techniques (before the advent of MRI) was used for pain management, CT-based imaging proved to be quite accurate for identification of targets in the ventromedial thalamus or periaqueductal gray matter. We now prefer high-resolution intraoperative MRI for recognition of pallidal, thalamic, and subthalamic targets.[17] *Table 9.6* provides a summary of our use of intraoperative imaging for functional neurosurgery over the last 25 years. MRI provides superior anatomic resolution to clearly delineate white matter tracts and gray matter nuclei. Multiplanar MRI facilitates preplotting trajectories to minimize risks. Currently, stereotactic MRI is used primarily for electrode placement during movement disorder surgery or for ablative sur-

TABLE 9.6. Functional stereotactic brain surgery, University of Pittsburgh Medical Center–Presbyterian, 1979 to 2007

	No. of Patients
Pallidotomy	147
Thalamotomy	72
Deep brain stimulation (movement disorders)	98
Depth electrodes for seizures	95
Deep brain stimulation (chronic pain)	24
Cell transplantation	20
Mesencephalotomy/capsulotomy	4
Total	460

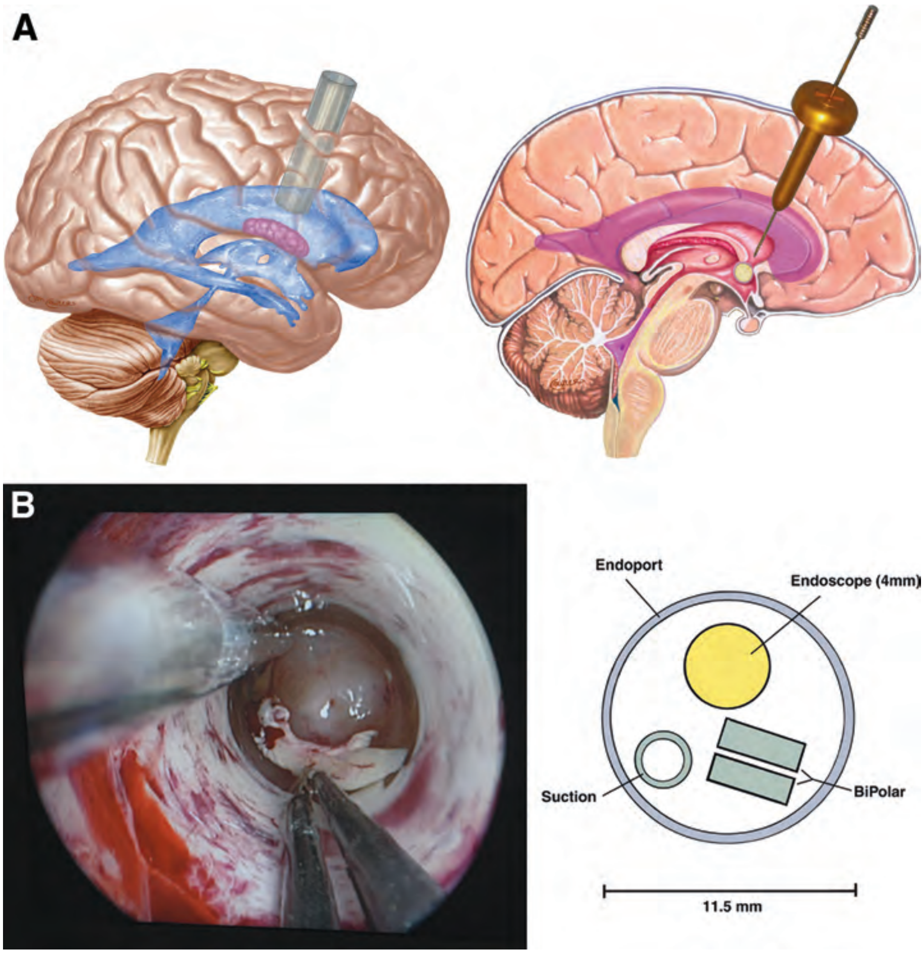

FIGURE 9.7. *A*, Stereotactic endoscopic resection of a colloid cyst is performed through an 11-mm conduit and a 22-mm trephine craniotomy. *B*, The endoscopic view into the third ventricle (left) with its diagrammatic representation (right).

gery.[12,16,17] In principle, neurostimulation has the significant advantage of reversibility with regard to side effects in comparison to lesion (ablative) surgery. Furthermore, ventroposterior pallidotomy or chronic stimulation in these structures may ameliorate bradykinesia and levodopa-induced dyskinesias. Additionally, "switching off" the subthalamic nucleus by neurostimulation has been reported to reduce rigidity, bradykinesia, and levodopa-induced on–off fluctuations. Pallidal surgery is less frequently used for Parkinson's disease but has become a valuable technique for dystonia. *Table 9.5* shows our experience with stereotactic functional neurosurgery. Using fusion software, we can merge preoperative MRIs with intraoperative CT for functional targeting.

Endoscopic-assisted Surgery

One of the most gratifying combinations of current technology has been the role of combined CT stereotactic frame-based assisted craniotomy coupled with endoscopic removal of selected deep-seated colloid cysts and brain tumors.[14] In our experience over the last 5 years, we switched to performing almost all colloid cyst removal or other intraventricular lesion removals using a small trephine craniotomy at the coronal suture region followed by stereotactic placement of an "endoport."[11] Through this 11-mm conduit, the visualization endoscope can be placed (*Fig. 9.7*). Standard or specially constructed microsurgical instruments can be used to totally remove colloid cysts or brain tumors in the third or lateral ventricles. The ability to do both intraoperative preplanning CTs as well as intraoperative postprocedure CTs has assisted us in our determination of adequate or complete resection of such lesions. From the experience of the senior author, the morbidity of this procedure remains low compared with comparable transcallosal or microsurgical transfrontal approaches.

Frameless Stereotactic Surgery

Beginning in the early 1990s, we began to evaluate the first generation of frameless stereotactic systems to assist localization and resection of mass lesions of the brain. First using the wand system, a mechanically assisted arm, with image integration, we recognized very early the potential for enhancement of lesion localization and resection assistance. Although this prototype had certain limitations, the concept was immediately obvious. We believe that the precision of frameless stereotactic surgery is significantly less than frame-based surgery (±2–5 mm versus 1 mm for frame-based procedures). For many tumor craniotomies, this is quite sufficient. One of the great advantages was the assurance of absolute precision of an appropriate craniotomy. During surgery itself, frameless technologies enhanced our ability to recognize tumor boundaries. One of the immediate practical aspects of this was the ability to limit the overall size of the craniotomy because brain "exploration" using more cumbersome techniques, including intraoperative ultrasound, were no longer needed. It was at this point that the senior author switched to using trephine craniotomies with a linear incision for most tumors. Dr. Patrick Kelly kindly taught the senior author the technique of trephine craniotomy during a visit to the Mayo Clinic in the early 1990s.

Since that time, virtually every cytoreductive surgical procedure for an intra-axial mass lesion, for meningiomas, and for many cranial base neoplasms has benefited by successive generations of image-guided techniques. Although each of the systems has merit, we continue to see the improvements such as the ability to incorporate several imaging modalities (CT, MRI, functional MRI, magnetoencephalogram) using fusion algorithms to define targets. We use imaging compatible fiducials attached to the patient's scalp or new mask systems if the head is not rotated. At our university teaching hospital, thousands of patients have undergone image-guided intracranial and cranial base procedures.

Virtually all endoscopic procedures are done with image-assisted frameless stereotactic surgery. It has become a quality assurance mechanism that is universal and almost always used. The main benefit of this particular approach has been its assistance to the surgeon in refining access routes and in determining margins of resection. In addition, image-guided surgery facilitates recognition of important neurological or vascular structures adjacent to the lesion. Most importantly, it does not interfere with the surgical flow of the procedure. It has held true to the tenet that imaging adjuncts to surgery must improve the surgeon's skills. When new technology is used, the technology cannot become the focus of the procedure. The goal of the procedure remains to remove the lesion. Similarly, intraoperative evoked potential monitoring provides such assistance and does not in any way interfere with the flow of the procedure. In fact, these technologies have reduced the total surgical treatment time because of their ability to reduce the size of the access that is required. Registration of the patient's images is accomplished in only a few minutes after the patient has undergone final positioning in the Mayfield head holder.

Various manufacturers have redesigned freehand or probe holders during image-guided MRI and CT and frameless procedures. These products are reminiscent of some of the old burr hole-mounted systems first developed in the 1960s. This concept was reintroduced by Mark Caroll in the 1980s. Similar devices are widely marketed for routine diagnostic or therapeutic procedures. These include brain tumor biopsies or cyst management. Such procedures offer some benefit over the prior technique of a simple freehanded biopsy ("a shot in the dark"). After the emergence of frame-based stereotactic surgery, frameless stereotaxis was born. The benefit of frameless as opposed to frame-based stereotactic surgery is hard to assess. Frame-based systems allow you to preplot precise probe placement to identify the exact target to be biopsied and to assure rigid fixation. Burr hole or otherwise mounted stereotactic frameless systems with trajectory recalculations during the actual probe passage may be associated with a higher risk of morbidity. The learning curve for frameless stereotactic systems is rapid, whereas the training and educational needs for a neurosurgeon to become proficient in frame-based stereotactic system is greater. We believe that patients continue to benefit from the proper use of frame-based systems. This is especially true for deep-seated lesions in the basal ganglia, thalamus, pons, and medulla and for lesions in other high-risk locations of the brain such as the perisylvian area.

SurgiScope

One of the most elegant systems proposed for intraoperative assisted lesion resection was the SurgiScope (Elekta Inc, Norcross, GA). This robotically mounted image-driven microscope was truly an inspired technology (*Fig. 9.8*). The device could robotically position a microscope to a preplanned trajectory, had laser localization to pinpoint the area of proposed access, and could be repositioned continuously to assist lesion resection. Theoretically, it has all the benefits of the perfect tool: magnification, illumination, precision, image guidance, and robotics.[1,9,10] Our addition of this technology to a new operating room suite was one of the many advances which our institution invested significant financial resources

FIGURE 9.8. The robotic microscope (SurgiScope), with its stereotactic precision, is an elegant, but not user-friendly, technology.

in. We wish that this technology had proven more valuable and less frustrating. The use of the technology broke one of the first cardinal rules, i.e., the technology must assist the surgeon to do a better, more efficient and safer job. The SurgiScope proved to have such complexity that it required continual retraining of staff. Our inability to dedicate a single individual to be responsible for the system led to a series of difficulties relative to its use. The learning and relearning curve was too great. At the same time, the clearly simple use of other frameless stereotactic image guidance systems proved to be less time-consuming and easier to operate. The SurgiScope was eventually retracted into the ceiling of our operating room, where it sits forlorn. In an academic environment, pushing the frontier requires an investment in new technologies. Among the technologies that our program has undertaken, only the SurgiScope represents one whose promise was not fulfilled in clinical practice.

FIGURE 9.9. The new dedicated CT stereotactic operating room at the University of Pittsburgh Medical Center–Presbyterian (Courtesy of Burt Hill Architects.).

Development of a Dedicated Stereotactic Operating Room

In the late 1970s, our planning process for a new stereotactic operating room debated the value of biplane angiography versus conventional radiological imaging techniques. Fortunately, the rapid development of CT imaging clearly pointed to the need for a marriage between neurosurgical techniques and neuroimaging devices elegantly proposed by Swedish mentor, Professor Backlund. The CT scanner was inverted from its usual position so that the patient and the head came through the back part of the scanner into the main area of the operating room. We also integrated this with a ceiling-mounted fluoroscopic system, which could be swung over the end of the CT scanner bed to permit real-time fluoroscopic imaging, which was done to assist certain CT-guided stereotactic procedures, including transsphenoidal approaches. Similarly, the C-arm fluoroscope was also used in over 1000 patients who underwent percutaneous trigeminal neuralgia management (mostly glycerol rhizotomy) during the next 20 years.

During this interval, several thousand patients underwent CT-assisted stereotactic procedures. A routine stereotactic biopsy could be completed in 60 minutes (wheels in to wheels out). The entire procedure time was greatly improved by our lack of need to move the patient between surgical and diagnostic imaging sites. Various surgical procedures evolved, including the transfrontal stereotactic endoscopic-assisted craniotomy previously described. Because of changes in the field and advances in surgical and imaging technologies, the lifespan of an operating room utilizing such advanced technology is approximately only 10 years. In particular, we felt that this was truly related to the emerging and increasing role of endoscopic surgical management, especially for intraventricular and cranial base lesions. Accordingly, we set about redesigning a new operating room using new CT scan imaging technologies, eventually placing a 64-slice GE CT scanner with fluoroscopic capabilities (*Fig. 9.9*).

This expanded operating room suite also provides video-assisted surgical techniques for endoscopic surgery, permitting simultaneous minimally invasive procedures with almost real-time imaging. Because we do not have any of the issues associated with the high magnetic fields of MRI, the standard operation paradigm remained in place. No tools needed to be redesigned, no special instruments needed to be created, and anesthesia services remained the same. Again, our goal was to enhance the operation, not convert the procedure from one whose goal was surgical resection to another whose goal was image obtainment.

We evaluated the role of intraoperative MRI scan over these years but were concerned about low resolution of the resistive 0.1- and 0.3-Tesla versions. Most of the prototype units had poor image quality, often resembling ultrasound, and limited field of view. Certainly new systems have been developed based on pioneering efforts done in Canada, Minneapolis, Newark, New Jersey, and in Erlangen, Germany. These sites plus other centers have shown the potential abilities to better resect certain tumors. We believe that the primary thrust of intraoperative MRI to facilitate aggressive resection of glial tumors is problematic. Perhaps a small minority of clinically recognized gliomas, those with circumscribed tumors in polar or lobar locations, may have better outcomes after complete resection. Patients eligible for better resections probably get better resections using intraoperative MRI.

Our new operating room allows us to fuse preoperative or intraoperative MRIs and intraoperative and postoperative CT, especially valuable in functional neurosurgical cases in which electrodes are being implanted. This is facilitated by using the Surgical Planning System SPS (Elekta, Inc.), which allows image fusion of stereotactic, nonstereotactic, and other imaging output such as magnetoencephalogram and positron emission tomography.

TABLE 9.7. Indications treated by gamma knife stereotactic radiosurgery at the University of Pittsburgh (August 1987 to June 2007)

Brain Disorder	Number of Patients Treated
Vascular disorders	1303
Benign tumors	2753
Glial neoplasms	666
Metastatic tumor	2495
Functional targets	844
Miscellaneous tumors	318
Total	8379

The potential for new technologies continues to grow. Technologies such as focused ultrasound, which does not use ionizing radiation to inactivate a target or a tumor within the brain, remains a promising investigational technique. Obviously, issues such as the need for open craniotomy to be able to use focused ultrasound have yet to be solved.

Certainly one of the greatest roles for image-guided surgery, and one for which we rely almost exclusively on MRI, is stereotactic radiosurgery. The senior author has used five gamma knife technologies over the last 20 years at the University of Pittsburgh, including the U, B, C, 4-C, and Perfexion systems (*Table 9.7*). The experience at the University of Pittsburgh in more than 8500 patients was possible because of high-resolution imaging technologies that defined the targets for this closed-cranium stereotactic approach. In certain patients, both open stereotactic operations (for example, brain tumor cyst drainage) followed by reimaging and then gamma knife radiosurgery using the same frame application in the same patient occur on the same day.[40] This methodology has shown enormous benefits for a wide variety of clinical conditions, including brain metastasis, vascular malformations, and cranial base tumors as well as functional neurosurgery procedures such as trigeminal neuralgia and thalamotomy.

During the senior author's Van Wagenen fellowship in 1980 to 1981, he trained with Professors Lars Leksell and Erik-Olof Backlund, M.D., Ph.D. Backlund further convinced me that neurosurgery would have a fertile union with neuroimaging. From that union would come three children, therapeutic brain surgery, stereotactic radiosurgery, and endovascular management. To that union, I would add one additional child, endoscopic surgery. The union has been long-lasting and enormously beneficial to a huge variety of patients at our medical center. Image-guided surgery requires a group of technologies that assist our abilities to deal with a wide variety of brain and spine problems and to reduce patient morbidity. In today's era, the practicing surgeon or surgeon in training should never have to ask the question that we had to ask years ago: "Where is it?" or "How do I get there?"

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