Imaging in Stereotactic Surgery

17 General Imaging Modalities: Basic Principles

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Historical Landmarks and Principles

Although not based on imaging, the basic principle of stereotactic surgery started with the work of Zernov in 1890 [1]. A Russian anatomist, he developed a map of the brain cortex depicted in a hemisphere that, when attached to the human head, would keep a constant relationship with corresponding functional areas of the cortex. This instrument allowed placement of the craniotomy guided by the patient's symptoms [2]. Further studies of the function of the central nervous system and symptoms the diseases required a more precise approach than the one devised by Zernov. Precise placement of recording and stimulating electrodes in specific areas of the brain to unveil function of deep structures called for a mathematical approach, Horsley and Clark devised and reported it in 1906 [3]. The Cartesian coordinate system, X (lateral), Y (anterior-posterior), Z (cranial-caudal), was born and remains the basis of stereotactic surgery (*Figure 17-1*).

If one reads the original work of Horsley and Clark, a striking finding is seen to the modern eyes; no imaging is mentioned for targeting the deep structures of the brain of the experimental animal [4]. As imaging was not readily available at the time, the skull landmarks were used as stereotactic reference. X-rays had just been described in Germany by Roentgen in 1895, only ten years before the seminal description of the stereotactic technique through the collaboration of the two English scientists, a surgeon and a physicist [3,4]. As the information age was not as fast pace as it is today, years were necessary for the incorporation of scientific accomplishments to surgery.

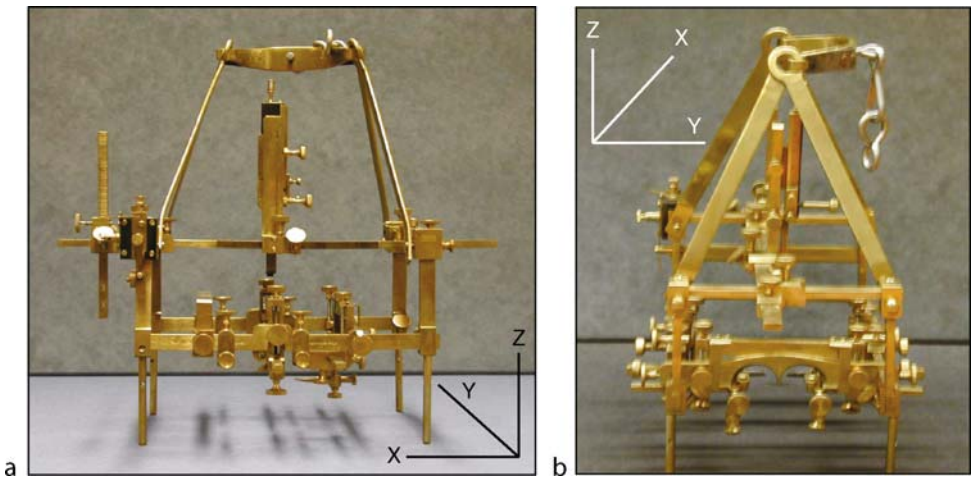
Although stereotactic surgery continued to be largely employed in the laboratory, using the Horsley and Clark's interaural line and midline as reference [5], these skull-based reference points were too variable to allow a safe determination of a target in the depth of the human brain [6]. Moreover, little was known about the function of the deep structures of the brain to allow intervention in humans. The natural path of animal experimentation was necessary for confirmation of the effects of lesioning of brain structures before one would propose interventions in humans. It was approximately 20 years after the initial studies of Horsley and Clark on the functional anatomy of the deep brain structures that the theory of basal ganglia motor integration was put forward by Spatz [7]. This theory spearheaded the first attempts of surgery in the extrapyramidal system to control movement disorder [8].

Ventriculography and the Stereotactic Landmarks

Parallel to these animal laboratory experimentations, imaging of the brain was being developed. Plain skull x-rays were followed by the description of ventriculography by Dandy in 1918 [9] and by angiography in 1927 by Egas Muniz [10]. These two monumental imaging modalities would dominate the landscape of stereotactic surgery for the following 50 years, firmly

Figure 17-1

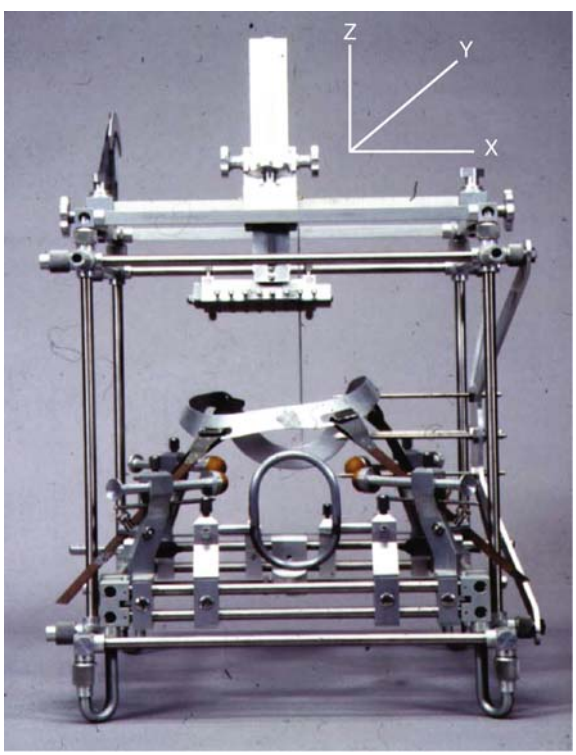
The Horsley and Clark stereotactic apparatus. Although the X, Y, Z coordinates' convention changed over the years, modern convention is as follows: the "X", "Y", and "Z" are right-left, antero-posterior and cranio-caudal displacement from the stereotactic space center respectively. (These pictures are a courtesy of the historical collection at UCLA Medical Library. This is the second Horsley and Clark apparatus assembled in history)



establishing the association of imaging and stereotactic localization. Since then stereotactic surgery has developed in parallel with imaging techniques. Early in their work, Spiegel and Wycis realized the importance of the stereotactic technique for morphological and functional neurosurgical interventions [6]. They described the need for improved imaging for visualization of deep brain structures, and actually developed methods of determination of stereotactic coordinates based on the calcification of the pineal gland, lately based on pneumoencephalography. The posterior commissure-pons line served as reference for their measurements. These measurements were used mainly for functional stereotactic surgery. While the development of functional stereotactic surgery was rapid with the perfection of their stereotactic frame (*Figure 17-2*), the morphological applications evolved slowly because the visualization of lesions in the brain became available only with the incorporation of angiography to the stereotactic technique. Although few neurosurgeons still use ventriculography for functional neurosurgery, its use is practically a historical legacy.

Figure 17-2

Spiegel and Wycis stereotactic device constructed in 1954, available at University of California in Los Angeles. As in Figure 19-1 notice the Cartesian coordinates, X, Y, and Z applied to human stereotactic surgery



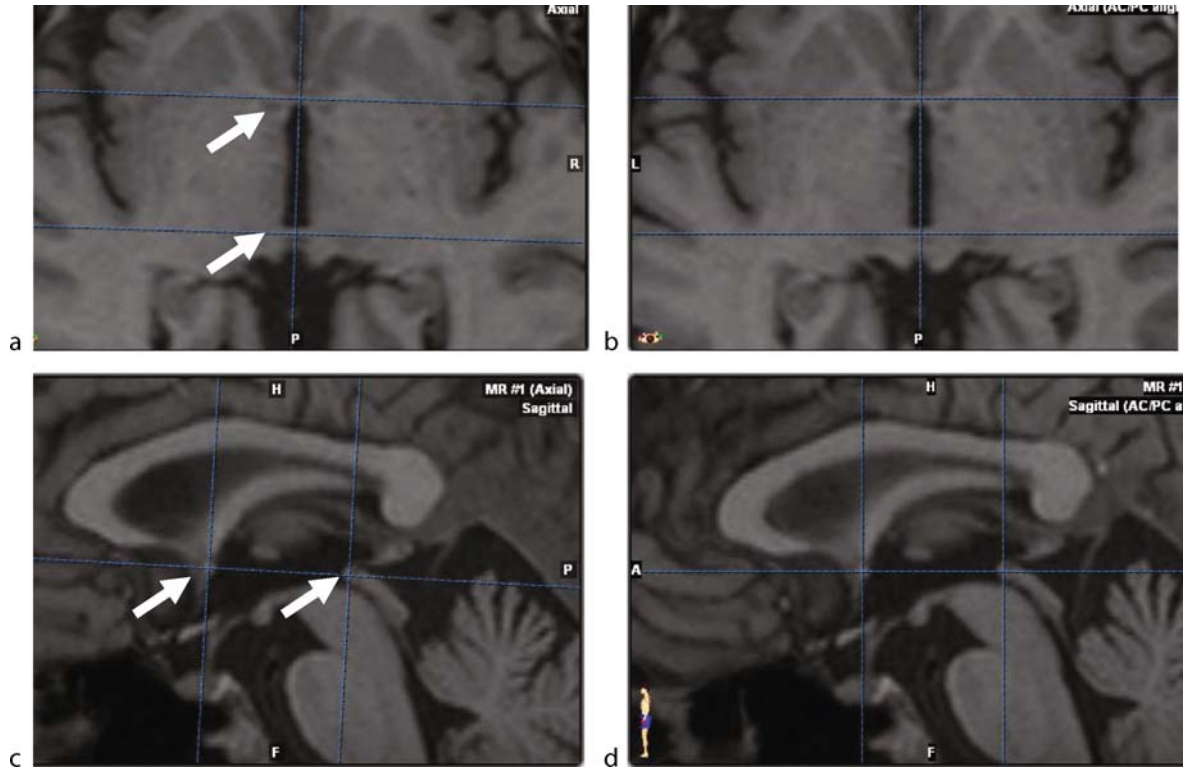
The main legacy of ventriculography and pneumoencephalography in stereotoactic surgery is the anterior-commissure (AC) and posterior-commissure (PC) line. AC is seen approximately 2 mm below the posterior border of the foramen of Monro, while PC is seen just cranial to the entrance of the aqueduct of Sylvius and just caudal to the pineal calcification. These two anatomical landmarks, now readily visualized on all plans of the MRI, specifically seen in the sagittal and axial plan [*Figure 17-3*], supported the development of the main atlases of the human brain, Shaltelbrand and Wahren [11] and Talairach's proportional atlas of the human brain [12]. Specific targets in the brain are described based on the distance of the midcommissural plane which is the intersection of the Cartesian coordinates dividing the brain into eight quadrants. Talairach used the length of the AC-PC line to develop the proportional atlas of the human brain widely used in epilepsy surgery.

Angiography

Angiography paralleled the developments in stereotactic surgery. Stereotactic angiography was introduced by Talairach's group [13]. Those workers dedicated several years of research to developing safe methods of inserting recording electrodes and radioisotope-loaded catheters and mapping the cortical anatomy by means of angiography. Their pioneer work using orthogonal

Figure 17-3

T1 MRI axial and sagittal sections passing through AC-PC planes. (a) and (b) are axial AC-PC planes, in (a) without correction for AC-PC plane angle, notice the arrows showing AC (*upper arrow*) and PC (*lower arrow*). (b) shows the MRI precisely at AC-PC axial plane as reconstructed by the stereotactic software. (c) and (d) are sagittal AC-PC planes, in (c) without correction to the horizontal plane, notice the arrows AC (*left arrow*) and PC (*right arrow*). (d) shows AC-PC aligned to the horizontal plane by the stereotactic software



approach to avoid the cerebral vasculature in functional and tumor stereotaxis established the grounds for several groups to use stereotactic angiography [14]. Specially trained neurosurgeons dedicated to epilepsy surgery followed Talairach's work. Techniques of angiography mapping of the brain promptly brought to computerized stereotaxis, initially through the use of superimposition techniques [15,16], later by digitization or scanning of angiographic films [17], and more recently in DICOM format, even with three dimensional angiography [18].

Talairach's group also concentrated on the understanding of the three-dimensional (3D) characteristics of the cerebral vasculature and its relationship with cerebral tumors aiming to develop diagnostic and therapeutic approaches, either with precisely placed craniotomy or by the use of stereotactic-guided placement of isotopes [14,19]. Because of the inherent two-dimensional nature of angiography, they relied on stereoscopic techniques to obtain the 3D information. The knowledge developed with stereotactic angiography led to the treatment of arteriovenous malformation (AVMs) with single dose radiation [20].

Angiography was not widely married with the stereotactic technique to approach intracranial lesions until the application of stereotactic radiosurgery for AVMs was described in 1972 [20]. Talairach described the implantation of isotopes for treatment of subcortical tumors using the blush of the angiogram [14], and Leksell described the use of external beam radiation directed stereotactically to obliterate intracranial targets and coined the term "Radiosurgery" [21]. Diagnostic procedures using the stereotactic technique were initiated only a decade later, despite the poor and only indirect visualization of structural brain lesions [22,23]. The number of morphological procedures surpassed the functional applications of stereotactic surgery with the advent of computed-imaging techniques which allowed direct visualization of the target [24]. Angiography sponsored the fast development of radiosurgery and approaches for determination of the seizure foci in epilepsy surgery.

Computerized Era

When computed tomography (CT) scan became available to stereotactic surgery, approximately 30 years after the first human stereotactic procedure, stereotactic surgery had a second revolution [24]. Now lesions could be visualized and the risk of approaching highly vascularized lesions became measurable. Biopsies of brain tumors, brachytherapy and especially radiosurgery dominated the time of stereotactic surgeons during the 1980s and 1990s [25]. CT scan also brought back the interest of neurosurgeons to lesioning the depth of the brain for symptom control in neurodegenerative disease such as Parkinson's disease, since the precision and the safety of the stereotactic method improved [26].

The functional stereotactic landmarks well seen in Dandy's ventriculography, which served the bases for all the electrophysiological studies of the specialty, were now well seen with the CT scan. The 1980s saw the resurrection of lesioning in the brain as a therapeutic option. The ventriculographic approach was compared with the computerized approach and the computerized era for functional neurosurgery was established [27]. However it was the morphological application of the stereotactic method that spearheaded this revolution and extension of the technique to common place in the regular operating room of the general neurosurgeon [28]. This came with the progressive abandonment of the stereotactic frame for image-guided surgery using triangulation methods and explosion of stereotactic radiosurgery as a minimally invasive technique for treatment of brain tumors and arteriovenous malformations [29,30].

Computer Tomography Stereotactic Principles

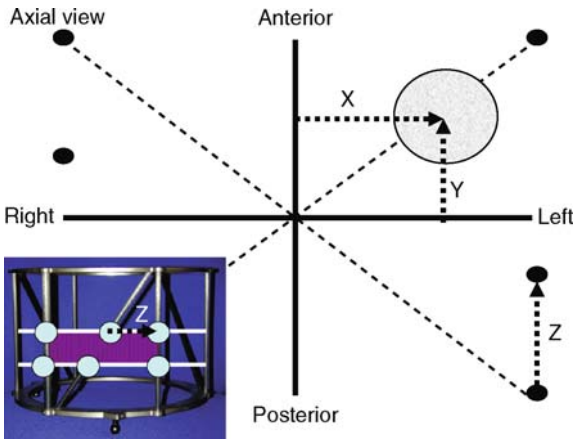
Hounsfield rightly received the Nobel Prize for medicine in 1979 for his description of X-Ray computed tomography (CT) in 1973 [31]. The imaging modality revolutionized neuroscience and the knowledge of brain pathology, function, and the ability of the stereotactic neurosurgeon to approach the brain safely. The technique was developed for visualization and not for precise calculation of intracranial targets. Therefore, years of work of stereotactic surgeons was necessary to bring this image safely into stereotactic surgery. As CT provided axial images only, stereotactic surgeons could determine only two coordinates from the slice of interest, i.e., where the target was located, either the pathology or the functional site to be targeted. By convention, the "X" became the lateral coordinate and the "Y" the antero-posterior. The vertical coordinate was not seen in the chosen slice, and the stereotactic surgeon had to devise methods of "Z" determination.

Initially stereotactic surgeons relied upon the movement of the CT scan table to calculate the "Z", however the manufacturers of the CT scans were not worried about the precision of movement of the table, since the scanners were built for diagnosis. Frames were developed to overcome this imprecise movement of the table. The best example of such strategies is the Laitinen's device which had transverse bars calibrated to correct the imprecision of the table movements [32]. It was not until the clever oblique bar introduced to a localizing box attached to the stereotactic frame by a graduate student at the University of Utah that the problem of the "Z" coordinate could be solved (*Figure 17-4*) [33].

The stereotactic frame with the localization box became standard for all stereotactic procedures, including functional and morphological, from fine lesioning of pathways in the brain, to implanting electrodes to biopsies and craniotomy [16,34]. All commercially available stereotactic frames were adapted for the use of the oblique fiducials for determination of the "Z" (vertical) coordinate. The accuracy of the method was compared to the most used frames and shown to be submillimetric [35]. CT is considered up to now the most precise method for determination of stereotactic coordinates. The nature of X-rays with its rectilinear path avoids the introduction of distortions in the calculations. Distortions are introduced when using magnetic resonance imaging (MRI).

Figure 17-4

Axial representation of the fiduciary system with explanation of the oblique fiducial of the stereotactic localizing box. The Brown-Roberts-Wells (BRW) localizing box allows for three-dimensional definition of a point in any imaging slice (insert). The 9 points fiduciary system became widely used because of the possibility to correct for frame misaligment. The X and Y can be directly extracted from the axial slices, while the Z is calculated using the distance between the oblique bar to the reference bar in each slice



MRI Principles

As the MRI scan became available and its geometric distortions were controlled [36–38], this imaging technique was preferred by stereotactic

surgeons [39,40]. Because it presents exquisite visualization of the nuances of the brain pathways and nuclei and the consequences of the surgery [41–43], it has revolutionized the approach of functional stereotactic surgery, no longer depending so much on ventricular landmarks, but relying on direct targeting of the structure needing functional modification [44].

Brain-function visualization is the next frontier on the development of stereotactic targeting. The incorporation of the chronic electrical stimulation as a therapeutic approach, initially for treatment of behavioral disorders, then for refractory chronic pain and movement disorders and more recently again for psychiatric disorders, has decreased the serious complications of the approaches in the depth of the brain. Progressively lesions of nuclei and pathways are being replaced by the ability of electrical stimulation to modify function by focally modulating neurons and brain networks. Functional imaging becomes more important for modulation of functional diseases of the brain, such as the neurodegenerative disease, genetic pathologies and brain damage by ischemic or traumatic injuries. Functional MRI and the ability to operate inside the magnet using frame [39,41] or frameless techniques brought new opportunities for functional neurosurgery [45–47].

In the arena of morphologic stereotaxis the revolution was on imaging localization of tumors and malformations in the brain needing intervention. Initially stereotactic surgery was used for simple needle biopsy [48], then to aid resections and guidance [16]. Here also functional imaging and the exclusive visualization of fibers related to lesions are revolutionizing surgical resections and targeting functional stereotactic surgery (*Figure 17-5*) [49,50]. These important imaging developments are readily applicable to stereotactic radiosurgery (SRS), currently representing substantial, if not the major application of the stereotactic technique [51]. Initially SRS was dependent on the stereotactic frame [52] and now, similar to surgical resection, it is becoming independent of the frame approach [53].

Positron Emission Tomography and Stereotactic Procedures

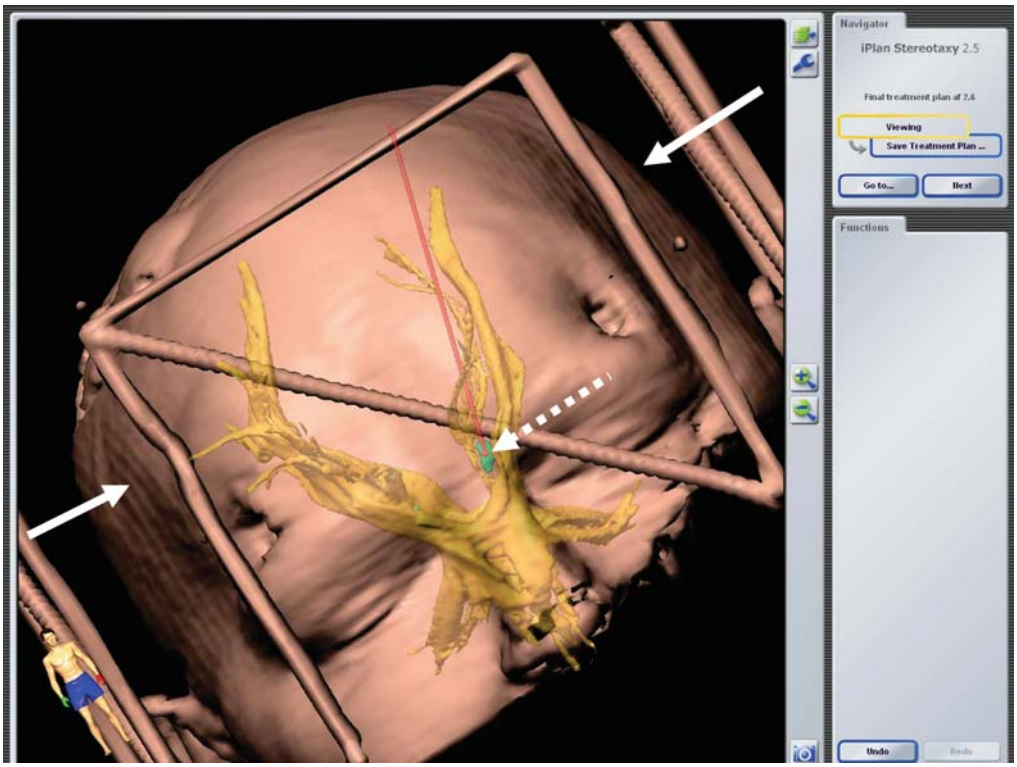
CT and MRI scans sometimes do not adequately demonstrate the regions of interest for the stereotactic procedures. Molecular imaging, capable of demonstrating pathologies not seen in morphologic imaging can complement the needs of stereotactic surgery. Positron emission tomography (PET) adds this important metabolic information, and when incorporated by fusion with CT and MRI, may allow more accurate targeting and treatment planning in stereotactic radiosurgery, tumor resection, and biopsy.

PET in Morphological Stereotactic Surgery

Most PET scans use a radiotracer made up of a common metabolite, such as glucose or an amino acid, attached to a radioisotope such as 18F (Fluorine) or 11C (Carbon). The 18F-FDG (fluoro-deoxy-glucose) PET is most widely used, and when combined with CT or MRI, will demonstrate with exquisite anatomic precision regions of increased glucose metabolism. Since neoplasms and inflammatory lesions often have high glucose uptake matching that of the brain, differentiation of a lesion from normal surrounding brain may be limited. The amino acids, however, are selectively more utilized by neoplasms than normal brain. The 18F-DOPA (fluoro-phenylalanine) and 11C (Carbon) methionine PET scans utilize amino acid molecules, and have demonstrated increased radioactivity in neoplasms, when compared to normal brain [54,55]. Extent of surgical resection or radiosurgery targeting will sometimes

Figure 17-5

3-D frame and fiber tracking of the pyramidal system used for subthalamic nucleus targeting (*traced arrow*). Notice the distortions that can happen in fiducial system of the stereotactic localizing box (*full arrows*), reconstruction with iPlan software (BrainLab, Germany). This is a Leksell frame with copper sulfide liquid in the fiducial system (Elekta, Sweden)



be modified significantly by incorporation of PET on CT and MRI imaging [56–58].

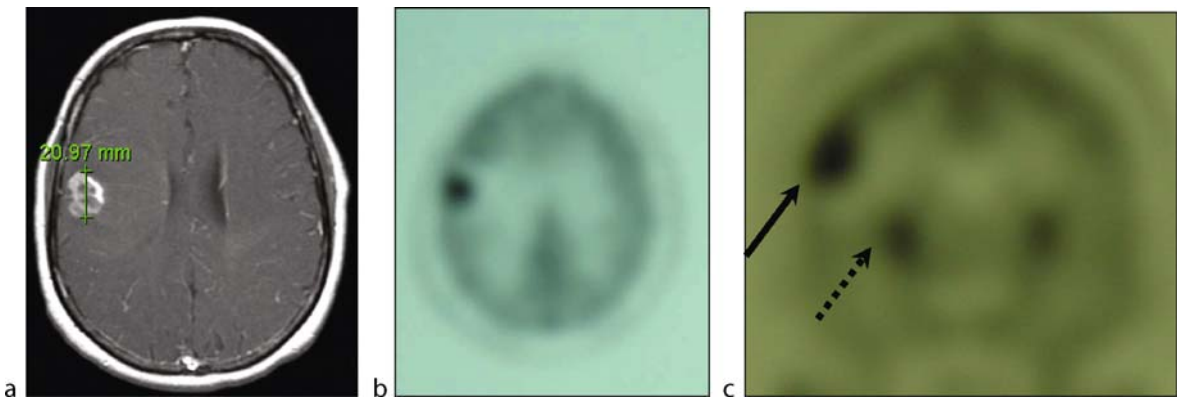
Fluorodopa PET, C-methionine PET, and other amino acid-based PET scans have proven to be more effective than FDG-PET for imaging of neoplasms [54,59]. Fluorodopa and C-methionine PET scans demonstrated sensitivity to low grade as well as high grade tumors, and may help to differentiate areas of radiation necrosis (*Figure 17-6*) [59,60]. PET scans sometimes demonstrate evidence of tumor recurrence before CT or MRI. They have proven to be most helpful in the management of gliomas [56–58], but also useful in treatment of other malignancies. It can be of help with pituitary adenomas [61], meningiomas, and parasellar lesions, where proximity to the cavernous sinus makes differentiation of tumor from normally enhancing structures difficult. PET has proven to be helpful with spinal cord tumors [62,63], particularly in the presence of instrumentation or in the patient not able to tolerate MRI (pacemaker or electrical stimulator) in preparation for radiosurgery.

PET Scans in Functional Neurosurgery

The PET characteristics of brain anatomy under normal and abnormal conditions have provided clues to a better understanding of brain anatomy and physiology. Changes on PET scanning related to deep brain stimulation have added to the still rudimentary body of information relating

Figure 17-6

Fluorodopa-PET to differentiate tumor recurrence from radiation necrosis. Nonsmall cell carcinoma brain metastasis treated with radiosurgery using 16 Gy prescribed to the 90% isodose line. (a) T1 MRI with gadolinium showing lesion growth with central hypo-intensity, possibly radiation necrosis. (b) Fluorodopa PET performed one year after the treatment and at the same time of the MRI in (a). (c) Coronal PET showing higher uptake of Fluorodopa in the lesion (*full arrow*) than in the basal ganglia (*traced arrow*), consistent with tumor recurrence. Histology of the resected specimen showed nonsmall cell carcinoma with focal necrosis



to pain, movement disorders, and behavioral problems. The noninvasiveness of PET makes it a valuable research modality. Striatal as well as extra-striatal dopaminergic activity in neurological and psychiatric disorders have been studied using PET biomarkers [64]. The PET tracers are very important in advanced research on problems of early and more specific diagnosis of major movement and psychiatric disorders, physiology of the dopaminergic system, evolution of disease processes, and response to medications and surgical interventions [65–68].

FDG-PET studies in patients with major depression have demonstrated increased glucose metabolism in the left amygdala and frontal limbic pathways, with evidence of decreased amygdala metabolism under antidepressant drug treatment [69] and/or vagus nerve stimulation [70]. Similar PET responses have been reported with deep brain stimulation of the anterior limbic system, such as the subcallosal cingulate gyrus [71]. These findings are consistent with the findings of PET blood flow studies in depressed patients by Mayberg et al. [72,73]. Mayberg et al. used the findings of increased blood flow in the sub-genual cingulate cortex, area AcG25, to realize a target for deep brain stimulation to control the symptoms of medically refractory major depression. Mayberg et al's early work demonstrated the integral role played by the subgenual cingulate cortex in both, normal, and pathological shifts in mood [73]. Increases in limbic and paralimbic blood flow (as measured using PET) occur in the subgenual cingulate cortex and anterior insula during sadness. There is a significant inverse correlation between blood flow in the subgenual cingulate cortex and right dorsolateral prefrontal cortex [74]. A clinical response to antidepressants is associated with limbic and striatal (subgenual cingulate cortex, hippocampus, insula, and pallidum) decreases in metabolism and dorsal cortical (prefrontal, parietal, anterior, and posterior cingulate cortex) increases in metabolism [69,72].

In 2005, DBS electrodes were bilaterally implanted in the subgenual cingulate cortex [75] of 6 patients with medically refractory major depression. When stimulation was on, patients reported positive emotional phenomena. In the acute postoperative period the patients experienced reproducible increases in activity and mood scores, changes that failed to occur during sham stimulation. Chronic stimulation at high

frequency, probably leading to suppression of function in the site, resulted in significant response and remission of depression in 4 of the 6 patients at 6 months. These well conducted studies showed the effectiveness of PET findings to enhance the knowledge of brain function leading to diagnosis and therapeutic measures.

Anterior capsule deep brain stimulation has resulted in decreased (18) FDG-PET activity or decreased glucose uptake in the subgenual anterior cingulate gyrus and ventral striatum in a group of patients with refractory obsessive compulsive disorder [76]. OCD patients with hoarding behavior showed different patterns of cortical PET- FDG activity, compared to those with non-hoarding behavior [77]. Evidence is accumulating to support the use of PET in routine target determination and follow up of patients undergoing neurosurgical interventions for mental illness.

Advances in radioligand technology [78] have provided radioisotope labeled molecules that enable study of neurotransmitters (serotonin, norepinepherine, dopamine and glutamate) and their receptors with PET [79–82]. Patterns and intensity of uptake have added to our understanding of movement and psychological disorders. As an example fluorodopa-PET uptake in the putamen would be decreased in idiopathic Parkinson's Disease as well as in a Parkinson's-Plus condition. However, greater loss of striatal D2 receptors in Parkinson's-Plus on a (11)C-raclopride PET scan might help to identify the patient as being unsuitable for surgical treatment with stereotactic implant of DBS, pallidal or thalamic lesion. Radioligands and PET have advanced the study of neuroreceptors remaining a most valuable tool for ongoing studies and treatment of patients with motor and psychological disorders [83].

Image Fusion

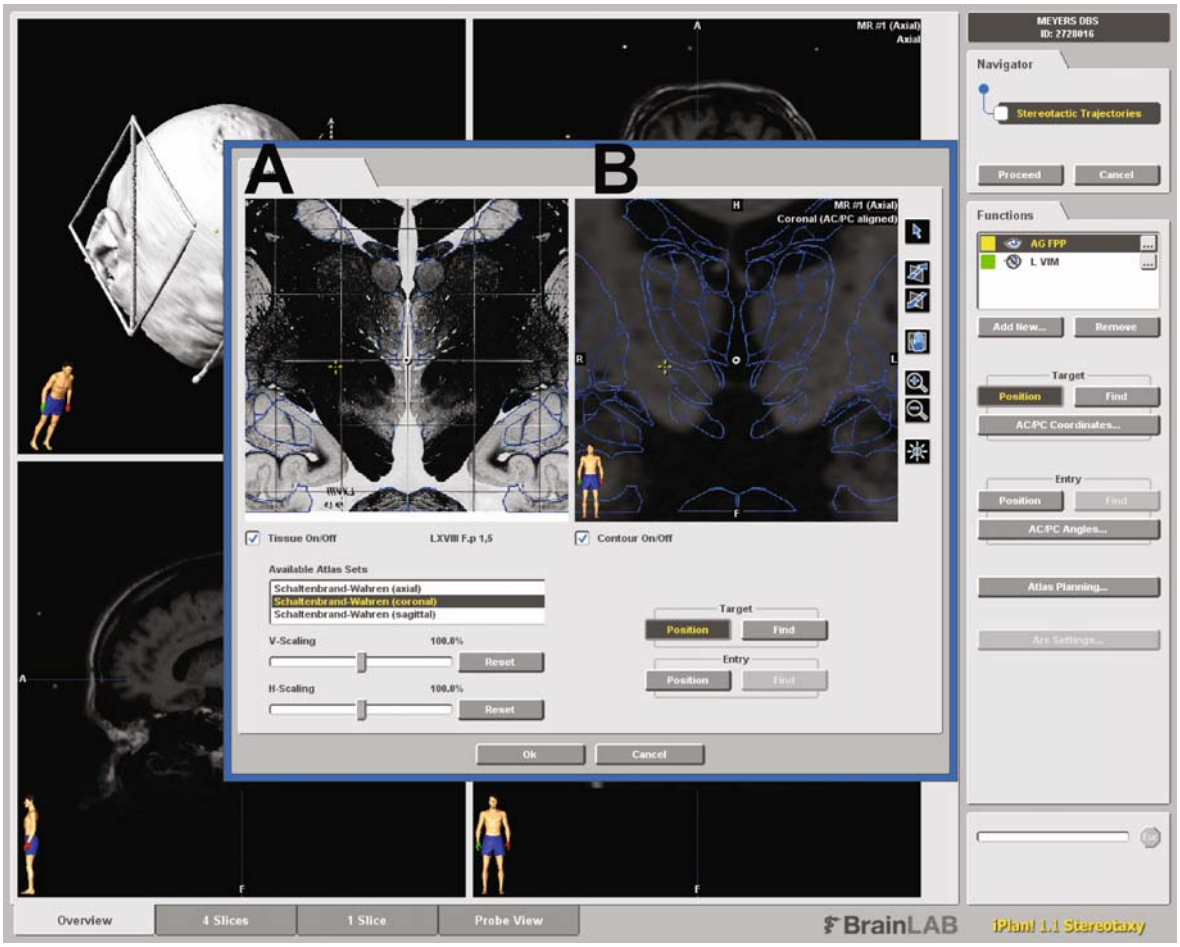
The ability to bring multimodality imaging to plan stereotactic procedures started with the work of Talairach. He obtaining information from angiography to avoid vasculature for seizure placement of electroencephalographic electrodes for seizure focus determination [13]. The attempt to bring MRI and CT into the stereotactic space determined by plain X-ray was started for stereotactic radiosurgery with fusion of imaging by photographic magnification manipulation [15]. These efforts have culminated with computerized fusion with software algorithms developed based on contours, image intensity, and voxel matching. These precise approaches have allowed gathering detailed information prior to the procedure, facilitating the surgery planning. Before these techniques were available, the patient had imaging with the stereotactic frame in place and multimodality approaches were unyielding. Now a portable CT scan in the operating room has obviated the need of elaborate stereotactic operating rooms. The fusion techniques offer also the opportunity of atlas information integration to the patient's image (*Figure 17-7*). Moreover, real time information on brain shift and possible complication during the operation are obtained while operating inside the magnet [39,41]. Fusion of multimodality images is very important for correction of distortions of PET, digital angiography and MRI scans. The portable CT in the operating room can offer this correction [38,84].

Image-Guided Surgery

The integration of multimodality imaging is possible without the stereotactic frame [85–87]. This capability has revolutionized not only stereotactic surgery but also general neurosurgery. It is now impacting in other specialties such as radiation oncology, orthopedic surgery, head and neck surgery and general surgery. Modern imaging technology brings presurgical information to the surgeon that obviates unknowns. Computer technology, using this information, provides that surgery can be performed virtually on a screen before the patient is even touched. In addition, surgery has advanced to a level

Figure 17-7

(A) Shaltenbrand-Wahren coronal plate. (B) Superimposition of the anatomy in (A) onto the corresponding MRI coronal slice by iPlan stereotactic software (BrainLab, Germany). Notice the adjusting sliding scale under (A) capable of matching the atlas with the MRI



where minimal invasion and maximal effectiveness is routine. The term 'guided surgery' in the modern sense, should be viewed as 'modern surgery'. Guided surgery', however, is still seen by many as the use of computerized imaging, or traditional X-ray-based stereotactic techniques described above to bring the surgeon precisely to the pathology being operated on. The pressures of competition and multimillion dollar malpractice law suits have driven the modern medical centers to invest heavily in technology. This in turn has driven the price of medical procedures to almost unacceptable levels. The hope is that applied technology can decrease the costs of each patient treatment. Image guided surgery is an area that may lead to substantial savings in medical dollars. The scope of the approaches and the realistic surgical undertaking may lead to shorter hospital stays due to fewer complications related to extensive surgeries, less need for long convalescent and rehabilitation periods, and, consequently, a faster return of the patient to the workforce. Ultimately, this results in decreasing the overall price of medical care. This concept has been exemplified with complex skull base disease.

These difficult tumors are treated now with transnasal procedures for skull base tumor resections [88] under real time imaging in the operating room, and followed by radiosurgery, reducing patient recovery time, decreasing morbidity, and offering the patient complete control of their disease [89].

The stereotactic developments throughout the 20th century as described in this chapter, spearheaded by the computerized imaging, provided remarkable noninvasive imaging techniques developed primarily for diagnostic studies. These techniques were adapted for surgery guidance with navigation using triangulation techniques [85–87]. Now infrared reflectors or magnetic field are used for real-time localization [90]. Fast computers and smart software packages permitted the introduction of these images to the operating field to guide the surgeon. Digital fluoros copy, ultrasound, computer tomography (CT), magnetic resonance imaging (MRI) and positron emission tomography (PET) are now brought to the operating room and combined with merging data set techniques, allowing the surgeon to take advantage of a wealth of information that was previously unavailable. The surgeons of the past relied upon the principle of "exposure, exposure, exposure", and their individual knowledge of gross anatomy to perform surgery. The surgeons of the present rely on their knowledge of anatomy, anatomical imaging, and functional anatomy to perform minimally invasive procedures and solve previously unapproachable problems [91].

Spine Stereotactic Surgery

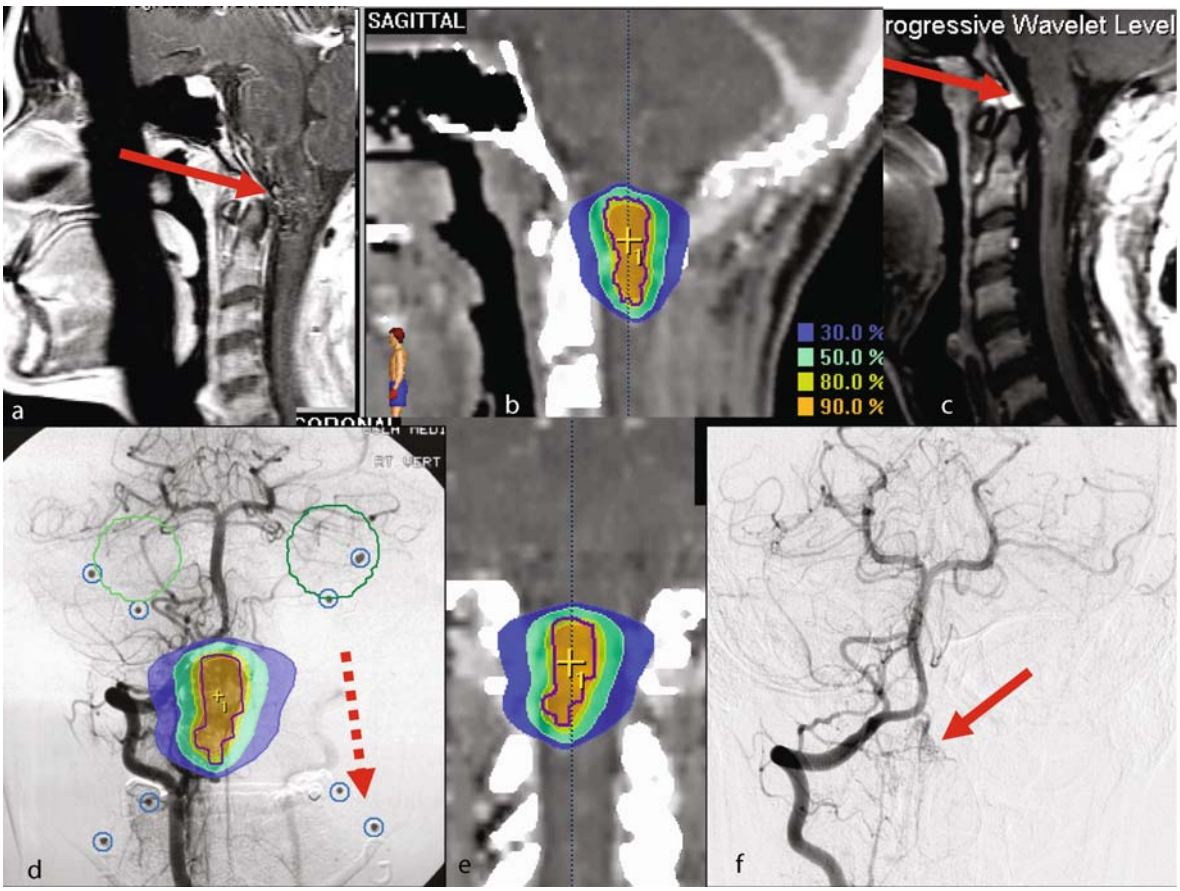
Invasive stereotactic fixation for radiosurgery of the spine was previously tried without acceptance from the stereotactic community [96]. The procedure proved to be too invasive and impractical to be largely applied. The development of image-guided surgery, as described above, provided the base for the development of the spine stereotactic technique. Image fusion and computerized image are now applied to stereotactic radiosurgery of spine lesions [91,94,95] and for placement of hardware. Completely noninvasive, fiducial systems use infrared triangulation and online image fusion of oblique X-rays and CT reconstruction to provide real-time movement tracking and targeting of lesions in the spine and surrounding regions [97,98]. The technology has reached precision to treat intramedullary lesions (*Figure 17-8*).

Future Directions

We are on the verge of perfecting real-time imaging in surgery [39,46]. During the past decade, the information brought during surgery by plain X-rays, fluoroscopy, and ultrasound was maximized and their limitations were established. Surgeons have now turned their eyes to the wealth of possibilities brought by portable CT scans and operating rooms equipped with interventional MRIs. MRI offers the possibility of not only exquisite anatomical information during surgery, but also dynamic changes of this anatomy associated with real-time changes in function. It also carries the advantage of not being harmful to the medical personnel, as are techniques dependent on isotopes or X-rays. The operating room with multimodality imaging, also known as operating room of the future, is a focus of studies in major medical centers. The logistics and real advantages of bringing a complex technology such as MRI to the operating room, or bringing the operating room to the complex MRI environment, has become a subject of symposiums on modern surgery [41]. The evolving field of functional MRI has brought the possibility of deciding before surgery the location of a fine function in the brain in relation to pathology (*Figure 17-9*). It has also allowed relating the complex wiring of the brain to the location of 'brain pace makers' (*Figure 17-5*

Figure 17-8

Medullary AVM in a 22-year-old woman who bled, developed tetraplegia and recovered after a C2–C7 laminectomy. (a) Sagittal contrasted T1 MRI before radiosurgery. (b) Sagittal CT with the radiosurgery plan (12 Gy, 90% isodose line, 1.60 cc lesion). (c) Sagittal contrasted T1 MRI 24-months post-radiosurgery. (d) Anteroposterior angiogram before treatment, notice the angiographic stereotactic fiducials (*traced arrow*). (e) Coronal CT showing the radiosurgery plan. (f) Anteroposterior angiogram post-treatment. Full arrows point the initial nidus (a), residual at 24 months (c) and residual at 26 months (f)



and *Figure 17-10*). All this information is readily related to imaging during surgery.

Products that integrate information from multiple imaging sources with diffusion of fluids through tissues, such as brain parenchyma for delivery of drugs after resection, have started to appeart on the market. This is achieved with stereotactic precision. Similar information is being generated by therapeutic thermal application, electrical current, and radiation. Laser or radiofrequency ablation, electrical stimulation with smart pacemakers capable of receiving and analyzing physiological clues, and radiation delivery with modulating capabilities are all novel approaches being developed [92,93]. The operating room of the future for 'guided surgery' and modern stereotactic surgery, requires real-time anatomical imaging technology related to function of the tissue under therapy at the moment of resection, lesioning or modulation [42,93]. This allows maximization of resection, drug infusion, electrical tissue influence, biopsy and the optimal use of radiation strategies to manipulate biological systems [92,101]. The patient should be least invaded and most helped by the modern stereotactic techniques.

Figure 17-9

(a) Functional MRI showing Broca's area (*traced arrows*) just posterior to an Arteriovenous Malformation (*full arrows*). The same AVM is shown on anteroposterior (b) and oblique (c) angiogram. The AVM removed through a craniotomy guided by stereotactic triangulation with the patient awake for complete speech preservation, lateral angiogram (d)

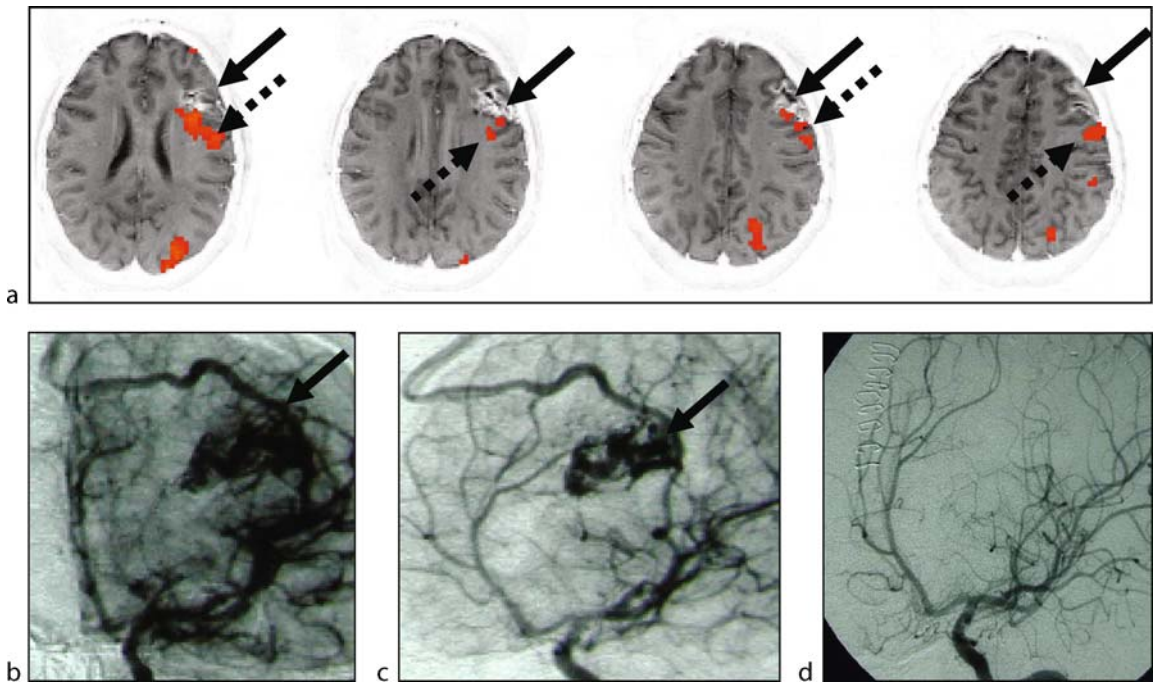
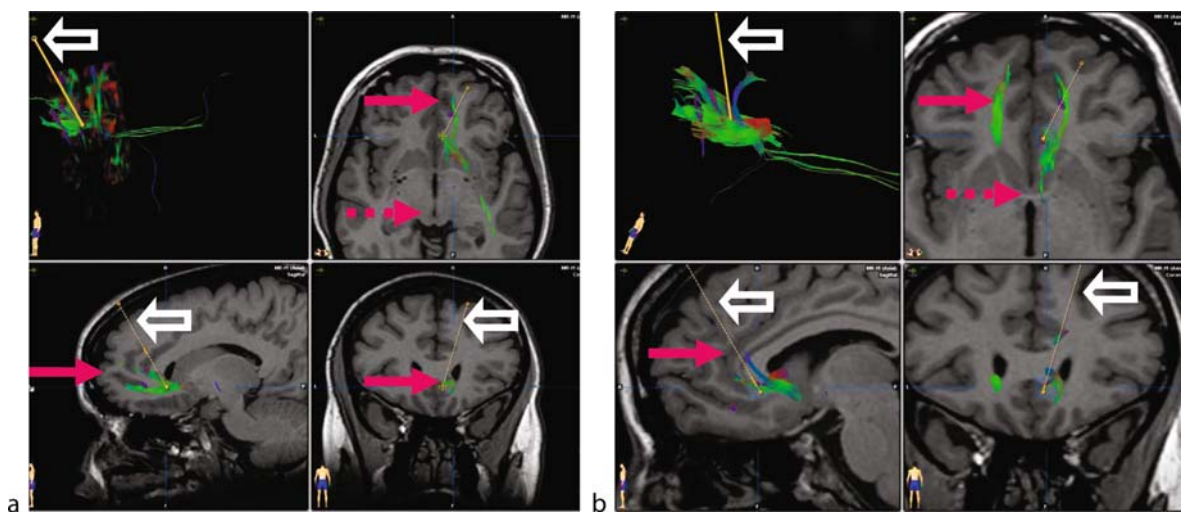


Figure 17-10

MRI fiber tracking from the subgeneal area (AcG25) recognized as the stereotactic target for implantation of deep brain stimulation electrodes for treatment of medically refractory depression, Notice the virtual electrode placement (*open arrows*). Notice the fibers going to prefrontal and orbitofrontal cortex and cingulate fasciculus (*full arrows*) [49,50]. (a) shows 3-D, sagittal and coronal reconstructions with axial MRI passing through posterior commissure, (b) same reconstruction passing through anterior commissure (*traced arrows*)



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