Article NIMHANS Journal

Recent Advances in Stereotactic Surgery

Volume: 14 Issue: 04 October 1996 Page: 339-347

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Abstract

Stereotactic surgery began almost a century ago but only recently has it come to be applied widely in the management of neurosurgical disorders. There have been several advances in stereotactic instrumentation and techniques in the past two decades, influenced mostly by the development of computer technology. Present day stereotactic surgical techniques include image guided surgery (both morphological and functional surgery), volumetric image guided surgery, frameless surgery, stereotactic radiosurgery and radiotherapy and robotic stereotactic surgery. The author discusses the indications for and the applications of these stereotactic techniques and their impact on the management of neurosurgical patients today and in the future.

Key words -

Brain tumour,
Computerised tomography,
Radiation therapy,
Stereotactic Surgery
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Stereotactic neurosurgery epitomises precision and accuracy in neurosurgery. As one can imagine, a surgeon working within the confines of an important organ like the brain, has little leeway in terms of precision. Every neurosurgeon wishes that the chosen target within the brain whether it be a tumor or any other lesion, should be reached quickly, precisely and by causing the least possible damage to the surrounding structures. Stereotactic techniques provide the medium to transform these ideals into practical application.

The term "stereotactic" is derived from a combination of "stereo-" (GK.) which means "three dimensional" and "tactic" (Lat.) which means "to touch" [1]. Therefore, a surgical technique which allows the surgeon "to touch" a target using "three dimensional" coordinates accurately describes stereotatic surgery. The term "stereotactic" has now almost completely replaced the older term "stereotaxis" (GK. "arrangement"). The seeds for this form of surgery were sown as long ago as 1908, when Horsley and Clarke described a stereotactic apparatus to study the cerebellar function of monkeys. But it was only four decades later, in 1947, the Spiegel and Wycis, devised an appartus that could be used in humans. Their paper led to a flurry of activity in the field of stereotactic surgery and soon several stereotactic surgeons had produced their own instruments. Prominent among these was the stereotactic apparatus of Leksell which he described in 1949 and is still in use in a modified form. The initial stereotactic procedures were mainly limited to the alleviation of pain or movement disorders such as the tremor of Parkinson's disease (PD) by producing lesions in various deep seated structures namely the thalamus and midbrain. The fortunes of stereotactic surgery were therefore, directly linked to the progress in the drug therapy of these disorders, mainly PD. Stereotactic surgery reached its zenith in the late 1960s when it was not uncommon for large centres to have series of thousands of patients undergoing thalamotomy for PD [1]. The introduction of L-Dopa for the treatment of PD, in 1969 almost sounded the death knell for this form of surgery. Stereotactic surgery has gone into hibernation as it were in 1970s. The advent of computerised tomography (CT) and the "marriage" of stereotactic surgery and CT in the late 1970s led to its rejuvenation and it probably now enjoys more popularity than it ever has in its history.

Image guided stereotactic surgery

In the early days of stereotactic surgery up until the late 1970s, the intracranial structures which were to be approached stereotactically could not be directly "seen" but their location could only be deduced using certain relatively fixed landmarks within the head (the anterior and posterior commissures) which could be visualised with invasive contrast ventriculogram. Stereotactic atlases based on the study of sections of several normal brains provided the coordinates for structures such as the ventrolateral nucleus of the thalamus (target for lesioning for tremor). The use of CT and more recently magnetic resonance imaging (MRI) in conjunction with stereotactic surgery has provided for direct visualisation of the intracranial structures whether it be the thalamus or a mass lesion which has to be biopsied. CT and MR guided stereotactic surgery is referred to as image guided stereotactic surgery. To prevent artifacts in the CT and MR, older stereotactic systems had to be modified both it terms of their structure and material and newer apparatuses devised. Image guided stereotactic surgery is presently the most common application of stereotactic surgery. The most obvious advantage of using image guidance for stereotactic surgery is the fact that a lesion could be directly visualised and hence the site within the lesion most likely to yield a diagnosis on biopsy can be targeted.

Stereotactic surgery is based on the Cartesian principles which states that any point in three dimensional space can be located using three coordinates (anteroposterior, lateral and vertical) which are unique to that point alone. Therefore, if one could guide a probe to a defined set of coordinates in the three dimensional space of the cranial cavity it should lead one to the selected target. The three dimensional space that one operates in has, of necessity, to be related to a reference plane. This reference plane has to remain fixed to the patient's head throughout the procedure. Thus it is no surprise that all image guided stereotactic systems incorporate a Head Ring or Base Ring which is rigidly fixed to the patient's head during the surgery. Stereotactic surgery done with these systems is also referred to as "frame based stereotactic surgery".

A brief description of the components of typical stereotactic system and a stereotactic procedure follows [2]. A vital component of a stereotactic system is a Localising System which is attached to the Head Ring while the patient is undergoing the imaging procedure (CT/MR). The Localising System assists in obtaining the third dimension (most often the vertical coordinate) from essentially a two dimensional image (axial CT slice). The three coordinates (ap, lateral and vertical) of any chosen target within the head are obtained either from the CT computer itself or from a dedicated preprogrammed computer. The other important component of the stereotactic system is the Arc System which is so manipulated that once it is mounted on the Head Ring fixed to the patient, it can carry the probe or biopsy instrument to the target site. Some systems such as the Cosman Roberts Wells (CRW) system provide a Phantom Base which is used to simulate the intracranial target and check the coordinates of the Arc System to ensure that the target is in fact being approached. Some common features to all stereotactic probes are their blunt tip to prevent injury to vessels in their path and their fine calibre (1.2 mm to 1.8 mm inner diameter) which reduces the trauma to the brain tissue in the probe trajectory.

A typical image guided stereotactic surgery, which is done under local anaesthesia in most adults, begins with fixation of the Head Ring to the patient's head using self penetrating screws. Then a CT or MR scan is done using an appropriate Localising System attached to the Head Ring. The target is chosen in an appropriate slice of the image on the CT/MT monitor and the coordinates (ap, lat and vert) are obtained either from the CT/MR scanner computer itself or a dedicated computer. These coordinates are set on the Arc System and checked using a Phantom Base (CRW system) and finally the Arc System is mounted on the Head Ring, still fixed to the patient's head, and the desired procedure is performed. The procedure usually takes between 1 to 3 hours depending on its nature.

The common indications for image guided stereotactic surgery are outlined in Table I.

Table I - Indications for image guided stereotactic surgery

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1.**Morphological surgery**

Morphological stereotactic surgery for biopsy, aspiration, placement of drainage tubes and stereotactic craniotomy forms approximately 90% of image guided stereotactic work performed in most large centres. At our centre over a period of 8 years and 8 months (May 1987 till December 1995) we have performed 1055 stereotactic procedures and morphological procedures contributed 1024 of these.

Image guided stereotactic surgery impacts directly on day-to-day management of patients as it allows for the virtual elimination of empiric therapy of intracranial masses [3], [4]. Even with sophisticated imaging techniques such as CT and MR, the pathological diagnosis and hence the management of an intracranial mass lesion, is relatively imprecise. The magnitude of the errors of image based diagnosis can be any where from 6 to 30% [4]. For example, a deep seated intracranial mass which has the features of the tuberculoma can in fact be a glioma, secondary metastasis, lymphoma or a fungal or cysticercus granuloma. Because the lesion is deep seated, it may be relatively inaccessible for open biopsy and the morbidity of open surgery just to obtain a diagnosis may be unacceptably high. Thus one is forced to resort to empiric therapy in such a patient and in our country this would inevitably mean initiating empiric antituberculous therapy (ATT). Such a line of management could however cause several problems if the diagnosis of a tuberculoma was incorrect. It would not only unnecessarily delay specific therapy but also expose the patient to the potential side effects of the therapy (hepatitis etc). In the interval between initiating empiric therapy and second imaging procedure (done to look for a response to ATT) which is typically 8 to 12 weeks, the patient may also develop progression of the neurological deficits which may be irreversible even with specific therapy. On the other hand, if a tuberculoma is mistaken for a neoplasm and the patient advised radiation therapy, this could lead to disastrous consequences for the patient who has a potentially curable lesion (tuberculoma). So it is clear that in our country, more than in the developed countries, a histological diagnosis is essential before prescribing any treatment as inflammatory masses such as tuberculomas still constitute about 5% of all intracranial masses and they could be mistaken for other masses and vice versa.

There are several attractive features of image guided stereotactic biopsy. Chief among these is the fact than an intracranial mass in virtually any location can be biopsied. The procedure can be performed under local anaesthesia in most cooperative adults and therefore even patients unfit for general anaesthesia can undergo the surgery. There are few medical contraindications; uncorrected bleeding disorders, uncontrolled hypertension being some examples. As mentioned above, the biopsy site most likely to yield an accurate diagnosis (most often in the enchancing part of a contrast enhancing tumour) can be chosen on the scan. The diagnostic yield is quite high and is reported to be over 90 - 95% in most series [6]. The mortality and morbidity is also very low and is in the range of 0 - 1% for mortality and 1 - 4% for morbidity [7]. The figures for complications hold true even for stereotactic procedures for brain stem masses. Masses located in the brain stem were generally considered unsuitable for open surgery as it is associated with the high morbidity and mortality. But stereotactic biopsy and aspiration of brain stem masses is as safe as stereotactic procedures in other parts of the brain [8], [9]. Finally, there is very little risk of infection and duration of hospitalisation is also very short (2 days in most uncomplicated cases).

Image guided stereotactic craniotomy (open surgery) is also a major application of stereotactic techniques which enables the excision of small masses eloquent and deep seated locations with relative safety [10]. Finally, the precision of image guided stereotactic techniques can be utilised to place flexible or rigid endoscopes and this can lead to an element of "visualisation" to a "blind" stereotactic procedure.

2.**Functional stereotactic surgery**

Functional surgery is ablation or stimulation of structures such as the thalamic nuclei, to alter neurological function in patients with pain, movement abnormalities, epilepsy and psychiatric disorders (Table I). This form of stereotactic surgery which was the mainstay of stereotactic surgery in its early days had taken a backseat to morphological stereotactic surgery. But there is resurgence of interest in functional surgery since the recent reports of excellent outcomes following pallidotomy for PD [11], [12]. Psychosurgery has also fallen by the wayside and so has stereotactic surgery for epilepsy.

Volumetric image guided stereotactic surgery

Most image guided stereotactic procedures are "point oriented". In essence, the stereotactic system leads the surgeon to a chosen point in the brain, whether it is in a tumour for biopsy or localisation during open surgery. Volumetric surgery differs form "point based" stereotactic surgery in that the entire tumour volume rather than a point within it, is the focus of the surgery [13]. The tumour volume is identified on reconstructed stereotactic CT/MR and projected on computer within the operating room. Using lasers and an operating microscope (Which are linked to the computer) the resection is carried out through a cylindrical retractor mounted on the stereotactic Arc systems. The computer provides a continuous projection of the outline of the retractor (as a circle) and the position of the laser in relation to the outline of the tumour at any given depth. This enables the surgeon to excise deep seated tumours radically without damaging the surrounding vital areas of the brain.

Farmeless stereotactic surgery (graphic user interactive surgery)

One of the main drawbacks of frame based stereotactic surgery is the necessity of fixing a frame (Head

Ring) to the patient's head for the entire duration of the procedure. Besides the pain caused by this, the Head Ring and the Arc System also compromise the space available if the surgeon is performing a stereotactic craniotomy. The advances in image registration techniques and enhanced speed of computers has led to the concept of "frameless stereotactic surgery". The concept of doing away with the frame for stereotactic surgery is credited to David Roberts of Dartmouth Hitchcock Medical Center, Hanover, USA [14]. This from of surgery is also termed "Graphic User Interactive Surgery" (GUIS) [15]. GUIS "brings the operative field into continuous spatial registration with a graphic rendering of the operative field". The Head Ring which formed the reference plane for the coordinates in frame based stereotactic surgery is replaced by a set of markers (surgical staples) which are placed in the scalp and are visible on the CT/MR. The CT/MR images of the patient are acquired into a graphics computer workstation which is capable of 3 D reconstruction and rotating the images in several axes. The surgery begins with identifying the scalp markers on the computer generated reconstruction of the head (graphic display) and registering then using a registration device (localisation tool or pointer) which is touched to each of these markers. During the open surgery (craniotomy), the localisation tool or pointer (an articulated arm or wand), when touched to any point in the surgical field will be sensed by the system and its position is calculated and rendered in the 3 D reconstructed CT/MR images (the graphic display) on computer screen. The advantage of this display is that the surgeon can visualise the relationship of the point so touched to the surrounding structures which might not be seen in the surgical field but are clearly seen in the CT/MR images. This display thus enables the surgeon to avoid damage to any vital structure such as the brain stem or carotid artery.

GUIS differs substantially from frame based stereotaxy by providing continuous visual feedback which is unavailable with the frame based surgery. In that sense, frame base stereotactic surgery is essentially "blind" after the selection of the target on the CT/MR image.

There is vast potential for frameless stereotactic techniques. These range from planning craniotomies, stereotactic biopsy of lesions "under vision" and shunt tube placement. But by far its greatest potential is as a "navigational tool" using which a surgeon can traverse the hazardous course of eloquent structures in the brain on the way to a deep seated lesion. Similarly, its application in skull base surgery can be immense. In skull base surgery there are a multitude of vital structures in the operative field, but are hidden from the surgeon's eye by a covering of dura or bone. GUIS can help "uncover" these structures.

There are various commercial GUIS systems available and one of these has incorporated the system in an operating microscope.

Stereotactic Radiosurgery and Radiotherapy

Stereotatic radiosurgery (SRS) is the delivery at a single sitting of a high dose of radiation to a selected volume of brain tissue which has been localised in stereotactic space [16]. Stereotactic radiotherapy (SRT) on the other hand involves the same accurate delivery of radiation but using multiple fractions over a period of days.

Besides image guided stereotactic surgery, SRS and SRT are probably the most common application of stereotactic techniques. Similar to stereotactic surgery, the concept of SRS is now new. Lars Leksell in the 1950s coined the term "radiosurgery" and built a machine which used cobalt 60 to deliver the radiation. The first "Gamma knife", as it came to be called, was installed in Stockholm in 1968. But because of its prohibitive cost, SRS did not gain popularity till the more ubiquitous linear accelerator (LINAC) was modified for radiosurgery in the mid and late 1980s [17], [18]. Since then SRS has become an established form of treatment for certain specific indications. Presently, SRS can be performed using either the Gamma Knife or any LINAC based system (X Knife, Radionics Inc., USA). SRT can only be performed with a LINAC based system.

SRS differs from SRT and radiation therapy in general in that it does not depend solely on the radiosensitivity of the target tissue for its efficacy. Any tissue within the treated volume, whether it be made of rapidly multiplying cells or non proliferating tissue, is destroyed by the high dose of radiation (13 to 25 Gy). Another feature of SRS and SRT is the accurate localisation of the target volume using stereotactic techniques and the use of sharply collimated (focused) beams of radiation using collimators (4 mm to 40 mm in diameter). This results in a sharp fall off of radiation beyond the target volume so that the tissue adjacent to the target receives negligible amounts of radiation. Using multiple arcs of rotation in a LINAC based or multiple sources (201 to be exact) of Cobalt 60 in the Gamma Knife, all focused at the target volume, radiation dose to the intervening brain (between the scalp and the target) can be kept to the minimum. The planning of the arcs of delivery of radiation is accomplished using a graphics computer workstation with a high resolution monitor. The principles of planning for SRS or SRT is to avoid radiosensitive vital structures such as the eye, optic nerve, optic chiasm and brain stem. SRS and SRT can be done under local anesthesia in adults and hence nearly no patient is excluded because of poor clinical condition.

SRS begins with the application of the stereotactic Head Ring to the patient and then imaging the head with an appropriate Localising System (CT/MR/Angiography). CT is the gold standard and is usually combined with angiography for AVMs. After this the images (CT/MR/Angiography) are acquired into the computer workstation. The vital structures such as the optic nerves, optic chiasm, eyes, brain stem and the primary lesion are contoured by the surgeon on the CT/MR images in the computer. The computer then provides a 3 D reconstruction of these structures and the whole head. This reconstructed head can be rotated in any plane. The planning then proceeds after choosing a collimator size to cover the lesion. Care is taken during the planning to ensure that the arcs of radiation do not intersect vital structures. At the end the most suitable plan judging from the coverage of radiation to the periphery of the lesion (typically 80% of dose in LINAC based SRS) and radiation to adjacent structures, is chosen. Then the patient still wearing the Head Ring is brought to the LINAC suite and the Head Ring is fixed rigidly to the LINAC couch. The target point is brought to the isocenter of the LINAC using the LINAC lasers.

The indications for SRS are outlined in the Table II.

Table II - Indications for stereotactic radiosurgery

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Indications for SRS and SRT are still evolving but the first 5 categories cover the vast majority of lesions treated with this modality at present. SRS should not be considered to be a panacea as it has several limitations. Firstly, only lesions of less than 40 mm can be safely treated. The response to therapy is not evident for several months to years after the treatment. Delayed complications of radiation (approximately 5%) can occur between 6 months to 3 years after the treatment [19]. Presently, reducing the dose of radiation used in treatment, the use of better imaging and the use of high resolution computers to plan are contributing to a reduction in the radiation injury to adjacent nervous structures. Most importantly, long term follow up after SRS with CT/MR/angiography is necessary to ascertain the results of treatment (both the benefits and the complications).

Long term studies indicated that SRS results in the thrombosis of about 85% of AVMs over 2 - 3 years and control of 85 - 90% of benign tumours such as acoustic tumours and meningiomas [19]. For malignant tumours such as metastasis and malignant gliomas, its usefulness in prolonging life is yet to be conclusively proved [19].

Robotic neurosurgery

Industrial robots, appropriately modified, have been used to assist neurosurgeons or independently perform brain biopsies, since 1985. The data obtained from a stereotactic CT scan is fed to the robot which has an articulated arm. The robot is brought into the operating room and fixed to a floor mounting. It is then capable of pointing the end of its arm to the target and a surgeon can complete the procedure by drilling a hole in the skull and approaching the target through a probe. The main application of robotic surgery is to perform biopsies of intracranial lesions. It could also be used to insert radioactive substances into malignant brain tumours (brachytherapy) and for deep brain stimulation. In Grenoble, France, robotic surgery was performed in 900 cases and of these a majority of procedures were brain biopsies, insertion of depth electrodes to locate epileptic foci and insertion of electrodes for deep brain stimulation [20].

Conclusions

The impetus to the application of stereotactic techniques in routine neurosurgery has been provided by the development of powerful computers. These computer workstations capable of graphic display will soon become standard equipment in the operating rooms of major neurosurgical centres and all neurosurgeons will be forced to become familiar with computers. Stereotactic surgery is part of the growing field of "minimally invasive neurosurgery" and while image based stereotactic surgery and stereotactic radiosurgery are the two stereotactic techniques with which most neurosurgeons are presently conversant with, it will not be long before newer techniques like frameless stereotactic surgery and robotic surgery become part of routine neurosurgery.

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