Pitfalls in precision stereotactic surgery

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Abstract

Precision is the ultimate aim of stereotactic technique. Demands on stereotactic precision reach a pinnacle in stereotactic functional neurosurgery. Pitfalls are best avoided by possessing in-depth knowledge of the techniques employed and the equipment used. The engineering principles of arc-centered stereotactic frames maximize surgical precision at the target, irrespective of the surgical trajectory, and provide the greatest degree of surgical precision in current clinical practice. Stereotactic magnetic resonance imaging (MRI) provides a method of visualizing intracranial structures and fiducial markers on the same image without introducing significant errors during an image fusion process. Although image distortion may potentially limit the utility of stereotactic MRI, near-complete distortion correction can be reliably achieved with modern machines. Precision is dependent on minimizing errors at every step of the stereotactic procedure. These steps are considered in turn and include frame application, image acquisition, image manipulation, surgical planning of target and trajectory, patient positioning and the surgical procedure itself. Audit is essential to monitor and improve performance in clinical practice. The level of stereotactic precision is best analyzed by routine postoperative stereotactic MRI. This allows the stereotactic and anatomical location of the intervention to be compared with the anatomy and coordinates of the intended target, avoiding significant image fusion errors.

Key Words: Magnetic resonance imaging, precision, stereotactic

INTRODUCTION

In 1906, Clarke and Horsley published a landmark paper describing a topographical method of precise navigation within the brain of an experimental animal. Their mechanical frame allowed precise delivery of a probe to deep-seated structures in 1-mm steps in all three planes. This powerful tool was initially hampered by the lack of in vivo imaging that could visualize relevant anatomy within the stereotactic space defined by the frame. Punctate electrolytic lesions were created to mark the locations of unipolar or bipolar stimulation sites. The observed physiological responses were then linked with the precise anatomical location after the animal was sacrificed some weeks later.

Since these early beginnings, numerous technological advancements have been adopted to improve accuracy and precision of stereotactic interventions. Ventriculography was combined with the stereotactic technique by Spiegel and Wycis to estimate the location of specific intracranial structures in patients. Various
surrogate markers were then introduced in an effort to refine initial surgical targeting. These included recognition of neural firing patterns recorded with microelectrode techniques as well as characteristic electrical impedance patterns recorded from the tip of a probe as it traveled through diverse brain tissues.

Technological advances have culminated in the advent of stereotactic magnetic resonance imaging (MRI), a tool that permits in vivo stereotactic localization of visualized pathological and anatomical structures, both before and after the surgical intervention.

SURGICAL ACCURACY AND PRECISION

Surgical accuracy is a measure of the degree of veracity or proximity of the intervention to the intended target. Surgical precision is the degree of reproducibility or repeatability of the intervention [Figure 1].

Specific indications demand varying levels of accuracy and precision. For instance, the level of accuracy and precision required during functional neurosurgery when targeting the sensorimotor portion of the subthalamic nucleus for Parkinson’s disease is greater than that required when performing a biopsy of a large deep-seated lesion. Nevertheless, many of the principles that assist in improving precision and avoiding complications are relevant to any form of stereotactic surgery.

PREPARATION IS KEY

Pitfalls are defined as hidden or unsuspected dangers or difficulties. They are best avoided by considering known factors that may lead to potential problems. A thorough knowledge of clinical presentation, medical history, risk factors, and results of investigations, as well as an in-depth knowledge of the possible benefits and hazards of surgery are essential when considering patient selection.

Despite their relatively low incidence, hemorrhagic complications carry by far the highest risk of devastating neurological outcome in functional neurosurgery. Self-medication with aspirin or non-steroidal anti-inflammatory drugs may not be disclosed unless the physician asks specifically about their use. Age and a history of hypertension are associated with an increased risk of hemorrhage in functional neurosurgery.

As with other surgical procedures, patient selection and perioperative management play a crucial role in avoiding complications. However, this work focuses on the technical aspects of ensuring precision during a stereotactic procedure. The most reliable way of avoiding potential pitfalls is by having a surgeon who understands the basic principles of the technique and is confident with the equipment being used.

ENGINEERING PRINCIPLES OF STEREOTACTIC SYSTEMS

Contemporary stereotactic frames are based on the arc-centered principle that tends to maximize surgical precision at the target, irrespective of the surgical trajectory. Mini-frame or frameless navigation enjoys maximum precision at the entry point and then endeavors to replicate the planned virtual trajectory during surgery. However, small errors in trajectory can translate into significant errors at the target level [Figure 2].

An early study comparing the accuracy of frame-based with frameless techniques did not find any significant difference between frame-based and mini-frame techniques. However, error calculations were based on “fused” images, introducing errors that render the

Figure 1: Graphical representation of surgical accuracy and precision: (a) Accurate but not precise. (b) Precise but not accurate. (C) Accurate and precise

Figure 2: (a) The engineering principles of the arc-centred frame tend to maximise accuracy and precision at the target, irrespective of the surgical trajectory. (b) The engineering principles of mini-frame or frameless navigation maximise precision and accuracy at the entry point. Errors between planned and actual trajectory during surgery can result in significant errors at the target level.
methodology inappropriate in making such a comparison (see section on image fusion below).\textsuperscript{[27]}

In a subsequent well-designed study from Lund, the stereotactic targeting error during thalamic deep brain stimulation (DBS) was significantly greater with mini-frame than with frame-based technique (2.5 ± 1.4 mm vs. 1.2 ± 0.6, \( P < 0.05–0.001 \)).\textsuperscript{[8]} Nevertheless, tremor reduction was similar at follow-up, irrespective of the implantation technique. The apparent dissociation between stereotactic accuracy and clinical outcome may be due to the inability to visualize the motor thalamus on preoperative imaging (i.e. superimposed anatomical variability) and the relatively large size of the motor thalamus that makes it more lenient to inaccuracies of targeting.

Given the greater accuracy and precision of frame-based techniques, this work focuses on frame-based surgery. However, many aspects are also applicable to other forms of stereotactic surgery.

Surgical robots allow precise, deliberate, and spatially encoded movement; in essence, they are stereotactic instruments with the potential of achieving high levels of accuracy.\textsuperscript{[19,40]} Although surgical robots are not widely used in neurosurgical practice, their use is likely to increase over the coming decades. Precision in stereotactic radiosurgery also requires consideration of radiobiology and is outside the scope of this work.

**ATTENTION TO DETAIL**

Stereotactic surgery demands meticulous attention to detail during every step of the procedure.

**Equipment**

The surgeon should be familiar with the stereotactic system being used and knowledgeable about its strengths and weaknesses. Equipment should be checked prior to commencing a stereotactic procedure – a loose screw may result in geometrical inaccuracy that may compromise both the procedure and patient. As with any precision instrument, the stereotactic system requires regular maintenance and quality checks.

**Frame/fiducial fixation**

The stereotactic frame should be firmly secured to the skull to avoid any movement between image acquisition and surgery. Any such movement would result in targeting errors. A more perilous scenario would be if the head were to “slip” out of the fixation pins in the presence of an intracranial probe. On the other hand, overzealous tightening of pins should be avoided as this may result in penetration of the inner table of the skull and damage to intracranial structures.\textsuperscript{[5]} Use of a torque wrench may assist in frame fixation.\textsuperscript{[29]}

Due consideration should be give to the surgical trajectory and the frame placed such that the securing pins will not obstruct the surgical field. Particular consideration should be given when working with high-field MR machines and insulated posts should be used to prevent overheating of pin sites during imaging.

**Image acquisition**

“In clinical practice, brain imaging can now be divided in two parts: the diagnostic neuroradiology and the preoperative stereotactic localisation procedure. The latter is part of the therapeutic procedure. It is the surgeon’s responsibility and should be closely integrated with the operation.” Lars Leksell (1907–1986), 1985\textsuperscript{[46]}

The surgeon should supervise acquisition of stereotactic images. Thin-slice contiguous images through the target are required using a modality that allows optimal localization of the planned target. The use of contrast media will highlight vessels that can then be avoided during surgical planning. Rare instances of iatrogenic pseudoaneurysm have been reported following stereotactic procedures.\textsuperscript{[46]}

An effort should be made to ensure that the axes of the frame are in line with those of the scanner. A small spirit level will assist alignment of the frame axes with the scanning plane and will ensure that frame geometry is reproduced accurately on cross-sectional imaging. This is particularly important if the surgeon is relying upon manual calculation of target coordinates.

When obtaining a stereotactic MRI, the target region should be centered within the bore of the magnet since this is the region where MR distortion is the least. The field of view should include all the required fiducial markers and imaging should cover the intended entry point and target. Thin-slice contiguous imaging from entry point to target is also desirable.

MRI sequences designed for visualization of specific targets allow direct localization of anatomical structures. T2-weighted images may be used to visualize the subthalamic nucleus\textsuperscript{[24]} and modified proton-density images to visualize the globus pallidus.\textsuperscript{[25]} Collaboration between neurosurgeon and neuroradiology teams resulting in optimal MRI sequences that better visualize the relevant anatomy is time well spent.

**Geometric distortion and MRI-guided surgery**

Unlike diagnostic radiology, imaging for stereotactic surgery requires more than just visualization of structures. Although computed tomography (CT) imaging does not suffer from image distortion, anatomical detail is lacking in comparison with MRI. Inhomogeneities of the magnetic field within MR scanners can lead to geometric distortion of the acquired images.\textsuperscript{[61]} Inaccurate spatial representation would render images useless for the purpose of accurate surgical targeting. Geometric accuracy at the center of the MRI field tends to be...
A number of methods for correction of field inhomogeneities have been described. Manufacturers of modern MR scanners now incorporate software solutions that correct for distortion, resulting in greatly improved geometric accuracy of MR images. Phantom experiments at our institution have revealed that despite applying distortion correction algorithms, the MR image of the anterior middle fiducial on the Leksell frame is often displayed slightly posterior to its actual location (as yet unpublished data). Manually correcting for this error during fiducial registration significantly increases registration accuracy. Larger inhomogeneities that are more difficult to correct may exist around the base of the stereotactic frame. The “base ring” of the frame should therefore be placed low down on the head. It should also be appreciated that stereotactic calculations on coronal MR images may be less reliable than those on axial images since the inferior fiducials (closest to the base ring) may suffer from greater geometric inaccuracies.

With adequate care and quality control, high fidelity stereotactic MR images offer a true geometric representation of spatial arrangement with distortion errors in the subvoxel range. It is often stated that geometric distortion is least on 3D T1-weighted images; however, our experience is that distortion can be reduced to submillimeter values on other MRI sequences that allow visualization of anatomical structures relevant to DBS (as yet unpublished data).

**Image fusion – An under-recognized and significant source of targeting error**

Initial attempts to circumvent problems of MR distortion relied on fusing or morphing non-stereotactic MR data onto stereotactic CT images. This idea suggested that contrast-rich MR data at the center of the field could be supplemented with accurate fiducial localization with CT at the field periphery. Numerous commercially available software packages were developed and provide this facility. However, magnetic inhomogeneities are nonlinear whereas most fusion algorithms are linear. In addition, fusion between CT and MR images may result in fusion errors that often go undetected. When analyzed in detail, fusion algorithms are found to introduce mean errors of between 1.2 and 1.7 mm; larger errors of close to 4.0 mm may be expected in individual patients. The magnitude of fusion errors is at least an order of magnitude above those introduced by MRI distortion. Anatomical targeting on stereotactic MR images that visualize the fiducials and target on the same image eliminate fusion errors.

**Image manipulation and registration**

Some stereotactic systems allow manual calculation of the target coordinates from a selected target slice. However, more detailed surgical planning will require import of the images to a dedicated software platform that allows image manipulation and precise planning of both target and trajectory. Many software platforms provide a “navigation” view rather than a standard radiological view and this should not cause confusion in laterality. Where possible, registration of fiducials should be performed on the images where the target is readily visualized as this avoids introduction of fusion errors.

The default on some software platforms is to minimize registration error across the volume of the acquired images. However, the aim of stereotactic surgery is to maximize accuracy at the target level. Therefore, accuracy of registration at the target slice / level is more desirable.

**Surgical planning of the target and trajectory**

A surgical trajectory that avoids sulci and ventricles has been shown to reduce the incidence of hemorrhagic complications, presumably by avoiding the enclosed vessels. Planning an entry point to penetrate the crest of a gyrus is not sufficient to avoid sulci en route to the target. The individual complexity of the sulcal pattern and obliquity of the surgical trajectory require the image manipulation of the acquired stereotactic images with commercially available planning software that allows reconstruction along the proposed trajectory. Entry through the crest of a gyrus also prevents excessive cerebrospinal fluid (CSF) loss when opening the dura during surgery.

Moreover, avoiding relatively stiff anatomical barriers, such as the pia and ependyma, minimizes brain displacement by the advancing probe, thus improving surgical accuracy. Incursion into sulcus or ventricle can often be avoided by reconsideration of the planned entry point and, when performing DBS, can maximize the number of lead contacts within the target structure.

When considering stereotactic approaches to the brainstem, transgression of pial, ependymal, or tentorial surfaces can be avoided by considering ipsilateral transfrontal as well as contralateral transfrontal entry points; the latter allows access to more laterally placed pontine lesions. Both approaches allow the patient to remain supine during surgery, in a similar position to that in which images are traditionally acquired, thus preventing error due to positional brain shift. The transtentorial route has been virtually abandoned because of the increased risk of hemorrhage and trajectory deviation. The suboccipital transcerebellar approach is often used to access brainstem lesions. Care must be taken to ensure that the frame is placed low enough to allow the lesion to be visualized and to physically allow the required trajectory with a particular frame. Semi-recumbent, lateral, and prone positions
have been described to provide access, some of which may limit the possibility of surgery under local anesthesia. The suboccipital approach provides the shortest distance to the brainstem target.\(^{52,58}\)

When performing biopsy of a partially solid, partially cystic lesion, the solid portion should be targeted first to prevent targeting errors that would occur with significant brain shift after cyst aspiration.

The author uses a simple proforma to record the target coordinates and the “arc” and “angle” of the trajectory. The target coordinates obtained from manual calculations may be compared to those obtained from the planning station. This process offers a measure of redundancy and reduces errors in the transcription of coordinates. Some groups use a checklist in an attempt to standardize the procedure.\(^{12}\)

**Patient positioning**

As with other forms of surgery, patient positioning is a vital part of the surgical procedure. Performing surgery in a similar position to that adopted during image acquisition may limit postural movement of intracranial structures.\(^{12}\) When using a pericoronal approach, patients are positioned supine with slight head-up (around 15°) to encourage venous drainage, instead of a more upright semi-sitting position.\(^{39}\) A supine position is also likely to minimize the incidence of air embolism – a particular concern when patients are undergoing surgery awake without the raised central venous pressure afforded by the positive airway pressures of an intubated ventilated patient.\(^{7,28,34,41}\)

Rather than being fixed to the operating table with a Mayfield clamp, head and frame may be supported by a sand-filled vacuum pillow. In the event of an intraoperative seizure, this precludes the head being forced from the retaining pins and the resulting brain trauma by an indwelling intracerebral probe.
when using the Leksell frame, 160 mm when using the CRW) to ensure that the target is reached without being overshot. Equipment used for physiological monitoring (impedance, microelectrode recording) is tested.

After the coordinates are transferred to the frame, it is prudent to double check coordinates, ring, arc, and platform depth, and to perform a “reality check” on the patient to ensure that the planned trajectory and target are appropriate. When the entry point and trajectory have not been defined by the stereotactic plan, it is important to clearly mark the intended entry point on the scalp before draping to ensure that the entry point avoids eloquent cortex and venous sinuses.

**Extradural surgical procedure**

When a precise entry point has been planned, the surgical trajectory is re-established at each anatomical layer. A twist drill directed by the frame is sometimes employed when trephining the skull. However, a standard 14-mm burr hole provides access for hemostasis on the dura and the underlying pia and avoids transmission of excessive force to the frame. When not using the frame to direct the drill, it should be noted that when held perpendicularly to the skull, the drill axis is often different from that of the planned trajectory. This should be taken into account to ensure that the final probe trajectory avoids the bony margins of the burr hole [Figure 5]. Application of bone wax to the margins of the burr hole prevents air embolism and bleeding from bone.

**Minimizing brain shift**

Accurate stereotactic targeting does not necessarily result in accurate anatomical targeting. Brain shift or “brain sinking” has often been considered an obstacle to reliable neuronavigation based on preoperative images.\(^{[65]}\) Brain shift may be caused by CSF loss and pneumocephalus, postural movement of intracranial structures under the effect of gravity, or brain deformation due to the advancing electrode. A few millimeters of brain movement at the target region can adversely affect the targeting accuracy and the surgical intervention.

Up to 5.7 mm of subcortical shift has been reported during DBS procedures, predominantly in the direction of gravity.\(^{[17,66]}\) In one extreme example of brain shift during attempted DBS of the subthalamic nucleus (STN), the authors noted that the final lead locations: “were displaced in two patients … in the genu of the internal capsule … at the border of the internal and external globus pallidum; this was probably caused by brain shift due to a perioperative subdural accumulation of air after CSF leakage through the burr hole.”\(^{[66]}\) This degree of brain shift requires compensatory intraoperative adjustments and introduces added complication to the process of stereotactic targeting.

A number of surgical practices may be expected to reduce or avoid brain shift. Reducing CSF loss and pneumocephalus can be accomplished by the following: minimizing the time from dural opening to final DBS electrode implantation, flooding the burr hole with saline irrigation after dural opening,\(^{[45]}\) avoiding CSF suction,\(^{[46]}\) and sealing the dural defect (e.g. with fibrin glue) as soon as it is practical.\(^{[68]}\) Such measures can greatly reduce brain shift of subcortical structures in the vast majority of cases.\(^{[47]}\)

**Intradural surgical procedure**

The dural opening should ensure that the trajectory avoids the margins of the burr hole and should be large enough to admit the stereotactic probe whilst being small enough to prevent excessive CSF loss. The underlying pia is opened sharply and hemostasis secured before the probe is advanced into the brain parenchyma.

A sharp tip probe would theoretically result in less brain deformation; however, the authors favor a blunt tip probe in view of potential penetration, rather than displacement, of intraparenchymal vessels and the resulting hemorrhage [Figure 6]. Twirling movements while advancing the probe will result in a corkscrew action and greater trauma to the brain parenchyma if the probe is not perfectly straight. A smooth, steady advancement will allow displacement rather than rupture of any vessels encountered by the advancing blunt tip.

After the dura has been opened, high-flow saline irrigation and sealing of the defect with fibrin glue (Tisseel VH Fibrin Sealant, Baxter AG) will prevent excessive CSF egress – an important consideration when performing bilateral surgery.

**Brain mapping in functional neurosurgery**

Microelectrode recording (MER) is currently the most commonly used technique for physiological brain mapping. Despite the lack of available evidence that this approach improves clinical outcome, many groups believe that the target should be identified physiologically with MER. Some authors have suggested that the presence of brain shift demands the use of surrogate markers during precision stereotactic surgery in order to adjust for stereotactic and anatomical targeting errors.\(^{[13,23,44]}\) However, one must consider that it may be the mapping process itself that exacerbates brain shift since the use of multiple tracks, prolonged recording, or stimulation time would tend to increase CSF loss if adequate sealing of the burr hole is not achieved. In addition, surrogate markers of anatomical location may sometimes be misleading.\(^{[51,55,63]}\)

Some authors avoid brain mapping in favor of an MRI-guided and MRI-verified approach that minimizes brain shift.\(^{[20,26,45,69]}\) Others have approached this challenge by using intraoperative MRI to guide targeting after burr hole placement and brain slump has occurred.\(^{[37,59]}\) Results of open-labeled series suggest that such an image-
verified approach to surgery is likely to be as effective as other approaches.\textsuperscript{[9,20,32]} Conversely, the meticulous use of neuroimaging – both in planning the trajectory and for immediate postoperative verification of targeting accuracy – appears to carry a significantly lower risk of hemorrhage and associated permanent deficit.\textsuperscript{[69]}

**AUDITING ACCURACY AND PRECISION**

Postoperative stereotactic imaging best documents the accuracy and precision of an intervention – this allows a comparison of the intended target coordinates with the actual target coordinates of the surgical intervention [Figure 7]. Systematic targeting errors can be recognized and strategies adopted to significantly improve the precision and accuracy of subsequent procedures.\textsuperscript{[26]} Stereotactic fluoroscopy is often employed in theater to ensure that the probe has reached the intended target. Other groups perform stereotactic CT. However, only stereotactic MRI can assess whether the probe has reached the intended stereotactic and anatomical target.\textsuperscript{[26]} Acquired stereotactic coordinates of the surgical intervention can direct the single additional pass necessary for any relocation, thus minimizing the number of brain passes required to reach the intended target.\textsuperscript{[69]}

Safety is a concern when performing MRI in the presence of implanted DBS hardware and neurosurgeons should liaise closely with radiology and MR physicist colleagues to establish local practices and monitoring of MRI events. They should also be aware of the reality that the number of reported adverse neurological events in such situations is extremely low when sensible precautions are taken and many thousands of MRI scans have been obtained with implanted MRI hardware without adverse consequences.\textsuperscript{[71]}

**IMMEDIATE RETARGETING**

Imprecision of stereotactic targeting can be rectified immediately since the frame can be used to guide...
an additional brain pass. The previous stereotactic coordinates are modified according to the observed targeting error. Extension of the initial dural opening will allow a new corticotomy a few millimeters away from the first in the direction of the targeting error. This approach avoids the trajectory of the new track crossing that of the old and results in correction of suboptimal targeting.

CONCLUSION

Numerous stereotactic systems are currently used in clinical practice and a variety of intra-procedural techniques are employed with the aim of improving safety and precision of the surgical procedure. Comprehensive clinical assessment, appropriate patient selection, purposeful stereotactic visualization of the brain target, meticulous calculation of coordinates and trajectory, and a surgical team that is familiar with the basic principles of the techniques being employed are essential in avoiding pitfalls. Routine acquisition of postoperative stereotactic imaging documents the actual location of the surgical procedure and allows comparison with the intended target. Meticulous audit of the results will allow incremental improvement in the accuracy and precision of stereotactic surgery.

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