Review Article

NEURONAVIGATION: NEW ADJUNCT IN NEUROSURGERY

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Abstract:

Neurosurgery is an ever developing discipline. So many new technological adjuncts have been added and are being added. Neuronavigation is such a modern adjunct that has helped and is helping neurosurgeons and patients to have better surgery and outcome. This adjunct helps the neurosurgeon in determining or defining target areas, functional and anatomical high risk zones, landmark areas and trajectories. A brief review on basics of neuronavigation and its role in neurosurgery is discussed.

Keywords: Neuronavigation, Neurosurgery, Magnetic Resonance Imaging.

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Introduction:

Prior to the widespread advent of framebased/frameless stereotaxy, intracranial tumour surgery relied upon a (three dimensional) 3D conceptualization of anatomy from preoperative imaging using external anatomical landmarks such as the coronal suture and auricle as guide. Bone flaps were often planned with a margin for error, particularly when locating non-lobar tumors.[1]

Surgical navigation technology can be compared to the location and directional tracking system used in cars today. It is, in effect, a global positioning system (GPS) for the surgeon.

Neuronavigation provides intraoperative orientation to the surgeon, helps in planning a precise surgical approach to the targeted lesion and incorporation of the functional data provided by functional MRI and magnetoencephalography (MEG) with neuronavigation helps to avoid the eloquent areas. In addition, intraoperative MRI and updates of neuronavigation with brain shift enables radical resection of the lesion with the possibility of immediate control for tumor remnants.[2]

The use of computer-assisted systems in neurosurgery has evolved since the 1980s and neuronavigation was introduced in the early 1990s. The term neuronavigation is synonymous with:

- Image guided surgery (IGS)
- Computer assisted surgery (CAS)[3]

Challenges in Neurosurgery:

- To define the borders between tumour and brain
- To localize risks and functional area
- To confirm the quality/extent of resection
- To free from anatomical changes during surgery (brain shift)
- To have the better accuracy as possible (stereotactic procedures)
- To have guide-tools (biopsy-needle, DBS electrode)

Goal of Navigation:

With neuronavigation a neurosurgeon is able to visualize the scenario for surgery in a 3D model of manipulable computer data. In this way the neurosurgeon can "practice and check" the surgeries,

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try alternative approaches, assess possible difficulties, etc., before the real surgery takes place. Neuronavigation provides intraoperative orientation to the surgeon, helps in planning a precise surgical approach to the targeted lesion and defines the surrounding neurovascular structures causing minimal disruption or retraction to surrounding tissue. Using neuronavigation a neurosurgeon can detect accurately where he is working in a patient's body at any moment during surgery. Navigation helps to get the lowest medical traumatization combined with the highest therapeutic effect.

System Components

Several manufacturers supply serviceable neuronavigation systems. The fundamental components include:

- Computer workstation (pre-operative and intra-operative) with neuronavigation software and computer monitor
- Medical imaging input (either through a (Digital Imaging and Communications in Medicine) DICOM link or a portable digital data format)
- Optical digitizer with infrared emitters and two infrared cameras (Figure 1)
- Reference frame (secured to a head clamp) (Figure 2)
- Registration stars (frames) for surgical instruments
- Passive infrared reflectors (aluminum impregnated glass spheres)

Fig.-1: *Optical digitizer with infrared cameras and monitors.*

Fig.-2: *Registration star with clamp for Mayfield Headrest.*

Steps of Navigation

1. Data Acquisition

   Preoperatively, computed tomography (CT) or magnetic resonance imaging (MRI) is performed after 8 to 12 multimodality adhesive markers (IZI Medical, Baltimore, MD) are placed in a non-colinear fashion on the patient's head.[4]

   If each slice represents a known thickness of brain tissue (e.g. 2 mm) and the slices are contiguous without overlaps or spaces, the summation of the slices creates a 3-D reconstruction of the brain.[1]

2. Data Transfer

   Data can be transferred to the main data bank through intra/internet networking or even with transferring devices like pen drive or CD / DVD after which the digital imaging dataset is transferred to the workstation. Software enables the imaging dataset to be viewed in multiple planes and as a 3D reconstruction.[1]

3. Planning

   Surgical planning is conducted in the operating room while the patient is undergoing anesthesia. Typically, an entry point on the skin and a target within the lesion is selected. These points are represented on the screen by a hollow yellow cylinder, and the computer calculates the distance between the two points. Moving the cursor along the planned surgical path indicated by the yellow cylinder allows the surgeon to simulate the surgery and visualize structures that will be encountered. The pathway can be modified preoperatively as needed. The software provides other views of the selected surgical plan from a surgeon's perspective.[4]

4. Patient registration

   Once the patient is positioned appropriately for the planned surgical procedure, the patient's anatomy is registered by establishing spatial correspondences between the patient's head and the acquired images.[4]

   Registration is the process by which the preoperative image dataset is aligned with the real-time anatomy of the surgical space in the operation theatre. To prevent movement the patient's head is held in a Mayfield Clamp in view of the Optical Digitizer. Registration is then performed using either a point or surface alignment technique. (Figure 3) The co-alignment of these image dataset points within the surgical field achieves registration. Alternatively, anatomical landmarks identifiable on the imaging and in the surgical field (e.g. nasion, external auditory canal, orbital margins) can be co-aligned for registration. The accuracy of registration must be confirmed with visual checks. The computer monitor shows the pre-operative image dataset (usually in axial, coronal and sagittal planes with a 3D reconstruction view). Known landmarks on this dataset are identified in the surgical space using the default pointer tool (e.g. globes, orbits, external auditory meatus, tragus). The radiological and real-time anatomical landmarks should coincide exactly. If there are discrepancies, the registration process should be repeated.[1]

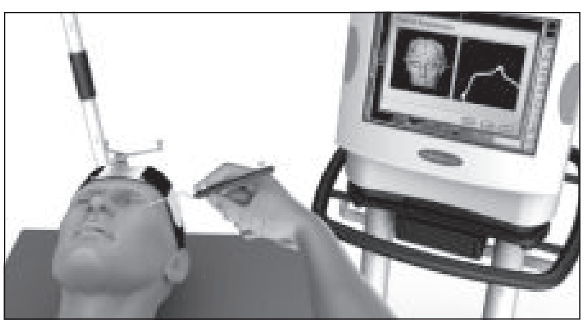

Fig.-3: *Patient register with pointer.*

5. Navigation

   Following registration, neuronavigation can be performed. Initially the pointer can be used to map out the site of a craniotomy flap. Care needs to be exercised when drawing a flap to account for parallax-type errors. These are minimized by planning a bone flap perpendicular, rather than oblique, to the bone. When working intra-cranially it is convenient to register familiar surgical instruments that can then be tracked as described above. The operating microscope can also be used as a surgical tool. The microscope has a passive reflector star secured in the line of sight from the optical digitizer. This permits the focal point of the microscope to be tracked in the surgical space and observed in the image space. The previously outlined target lesion (from preoperative planning) can also be visualized in a "head-up" display to help direct both the dissection to the target and to guide resection margins during the procedure.[1]

Neuronavigation Errors

Errors can occur at any stage during the neuronavigation process which can seriously compromise the accuracy. Diligence therefore needs to be observed at all stages to minimize, recognize and avoid errors. The use of intraoperative MRI scanning with all its associated inherent problems aims to recognize brain shift and enables an up-to-date imaging dataset to be used. Whilst time consuming and expensive such technology may have a role to play, particularly during resective procedures for low-grade gliomas.[1]

Advantages with Neuronavigation

- Navigate simultaneously in different image modalities
- Universal and accurate instrument calibration
- Powerful image composer, combines all relevant anatomical details into one image set
- High accuracy
- Smaller craniotomy and safer trajectory by decreasing the risk of functional morbidity[5]
- Identification of critical structures that are not visible via the usual surgical exposure[5]
- Improvement of functional outcome for surgery around eloquent brain areas[5]

Modalities of Neuronavigation

1. Computer-Assisted, Image-Guided Neuronavigation

By combining a computer with a detection system (light-emitting diodes [LEDs]), the location of a pointer tip (or likewise registered tool) within the surgical field can be viewed on a computer display where the surgeon uses the pointer like a 3D mouse to scroll through the images to point at specific areas within the surgical field. While enabling precise approach planning and localization, resection control is generally beyond the capacity of these systems, since they cannot account for intraoperative changes “brain shift”.

To overcome the limitations, various algorithms that characterize and calculate deformation matrixes[6 7] and identify various brain shift patterns were incorporated using intraoperative “sparse” ultrasound (US) data[8] which can be used to elastically deform preoperative MRI images. Albeit all these efforts advances were meager and the only option to provide precise updated navigation remains the integration of intraoperative images.

2. Intraoperative Fluoroscopy

For both angiography and spinal instrumentation, a major shortcoming was the planar imaging, providing indirect spatial information. Initial questions as to the spatial accuracy of these systems have been addressed in more recent generations and hybrid angiography ORs combining neurointervention and neurosurgery for neurovascular cases.[9]

3. Intraoperative Ultrasound

Intraoperative US (IoUS) was one of the first to be employed as an intraoperative imaging modality in neurosurgery.[10] Major developments includes duplex sonography, spatially accurate 3D ultrasound,[11] contrast-enhanced US[12] and the integration of US into navigation systems.[13 14]

Advantages are the dynamic, surgeon-driven, on-line character of the information.[13] The major indications are circumscribed lesions, such as metastasis, cavernomas, vascular pathologies, and for spinal intradural lesions.

4. Intraoperative Computed Tomography

For neurovascular surgery, intraoperative CT-angiography has the potential to provide information on vascular pathologies, and with perfusion CT, on potential vascular compromise. But even with the current generation CT, intraoperative CT remains less sensitive in detecting residual tumor. Furthermore, cumulative radiation exposure limits the number of potential intraoperative scans.

5. Intraoperative Magnetic Resonance Imaging

The intraoperative MRI is essentially a surgical tool. It is implemented to support surgical decision making. Thus the surgeon has to define his or her intention and the subsequent question, which primarily relates to the achieved extent of resection and complication avoidance.[15-17]

Presently intra-operative MRI is used primarily for gliomas and pituitary lesions,[15 18 19] but also for vascular[16] and epilepsy surgery.[20]

Which imaging to choose depends on the lesion’s imaging characteristics in diagnostic studies. For low-grade lesions, T2 and FLAIR images are the most appropriate.[15 17 21] For enhancement, pre- and post-contrast T1 images are acquired. Further sequences may potentially yield additional information, such as location of functional centers or fiber tracts using intraoperative MRI.[22]

Practical challenges in interpreting intraoperative images largely pertain to nonspecific contrast enhancement (“spread enhancement”). The surgical result is described by “removed percent of contrast-enhancing lesion.” Since contrast enhancement merely reflects the local breakdown of the blood–brain barrier, it is unsurprising that contrast spreads into surrounding regions over time. While almost inconsequential in diagnostic imaging, acknowledging this phenomenon is of major importance for intraoperative MRI (iMRI) to avoid over-resection. Thus scans for the initial neuronavigation-assisted resection should be acquired prior to surgery. When imaging is for resection control, pre- and post-contrast T1 images and subtraction are compared to identify residual contrast enhancement. New sequences capturing the dynamic nature of neovascularized areas, in particular dynamic susceptibility contrast-weighted perfusion MRI (DSC-MRI), provide more accurate intraoperative information than conventional contrast-enhanced T1WI.[23]

The shortcomings of image-guided navigation in detecting intraoperative changes were a major motivation to implement intraoperative imaging. Since surgery and imaging take place in different coordinate systems, the transfer of the images between these venues represents the crucial integrating step. Image-guided neuronavigation (IGN) provides this essential link.[15 24]

The first mobile 1.5-T MRI mounted on a ceiling rail system was developed and installed in Calgary.[16] Stationary MRIs in separated rooms are presently 3-T MRI units. The surgical site is a conventional operating theater. The patient is positioned on a surgical OR table with a floating top, which can be connected to the MR system. Either a rail system or a wheeled transfer table is used. The head- holder can be either separated from flexible surface coils, or integrated into the rigid imaging coils.[21 25] Newer modular designs include the MRXO[26] concept and the AMIGO (advanced multimodality image guided operative)[27] design.

For surgical navigation, the dynamic reference frame (DRF) is attached to the head-holder. The navigation system is registered, the craniotomy planning finalized. Imaging can be initiated at every point the surgeon deems feasible. The surgeon determines the imaging protocols based on presurgical imaging characteristics. The images are transferred to the navigation system as soon as they are acquired for updated accurate navigation.[15 24]

If residual tumor is identified, updated neuronavigation allows the precise localization for resection. The essential link between imaging and surgery is the computer-assisted IGN system. It represents the platform on which the pre- and intra-operative multimodal imaging information coalesces to enable surgical decision making.[24 28]

Fiber tracking has been employed in sophisticated ways, delineating the major fiber connections.[29] Spectroscopy has been used to guide stereotactic biopsies,[30] and with further refinement may yield information on resection borders in open surgery.[21]

6. Microscope Integration

   Recognizing that neurosurgeons perform most of their procedures while looking through a microscope and not the navigation screen, integration of pre-operative anatomical images with neurosurgery microscopes has recently been introduced. Some of the key features of this integration include:

   - Precise tracking of microscope view including zoom and focus information
   - Superimposed 3D projections, anatomical structures, targets and trajectories
   - Option of “Smart” Autofocus and robotic tool tracking for remote control of microscope

Discussion:

Neuronavigation has become a cornerstone tool in neurosurgery. Precise skin incisions, smaller craniotomies and easy localization of intracranial pathologies are fundamental applications of neuronavigation systems in neurosurgery in general.[31]

The neuronavigation is basically a miniature GPS. The neuronavigation systems are able to determine the position of the tip of a pointer in 3D space and to transfer the position into the appropriate CT or MRI data set in real time during the entire operation (in case of a microscope the focus corresponds to the tip of the pointer).[32]

Most of these systems have been demonstrated to be useful, especially for planning the surgical procedure. The neuronavigation system is a useful surgical-assisted device which can provide accurate information on the surgical site in real time. However, existing navigation functioned based on preoperative imaging has inherent fundamental problems involving the “brain shift.” In response, using intraoperative MRI or intraoperative ultrasound to confirm changes in brain morphology, image fusion technology enables a navigation system to adjust the images during an operation so as to resolve the problem. Three kinds of information, image, organ, and function, should be integrated to balance competing goals for maximum resection and ensuring safety. An important drawback is the relatively long image acquisition procedure (typically, a total of 20–60 min), which limits the practical number of acquired 3D scans allowed during surgery. A registration technique is also required to calibrate these intraoperative 3D scans to the patient.[3 33]

Recent promotion of collaboration between medical science and engineering has brought about significant advancement in the development of diagnostic imaging technology and surgical assisted systems. Using a high-resolution microscope, the operation requires high-accuracy technique that refers to the 3D brain image displayed on the neuronavigation system within a close tolerance of a few millimeters. On the other hand, the advancement of computer technology makes 3D virtual image technology more efficient, allowing the creation of images analogous to the clinical condition. Moreover, “brain shift,” the greatest weakness of a neuronavigation, was resolved with the development of image fusion technology which utilizes intraoperative MRI images for visualization of changes in brain morphology so that the navigation map can be adjusted during the surgical procedure. In a neurosurgical operation, this information integration among image, organ and function assures a good balance between maximum tumor resection for overall survival and provides a functional prognosis even for invasive malignant brain tumors. Furthermore, this innovation provides the momentum for development of surgical devices applicable even in the microscopic field.[3]

Dorward et al.[34] in 1998 found the mean shift of the cortex after dural opening was 4.6 mm, shift of the deep tumor margin was 5.1 mm, and shift of the cortex at completion was 6.7 mm during 48 operations. There was significantly greater shift at depth in meningiomas than gliomas and significantly less shift in skull base cases than other groups. They found that the preoperative image characteristics correlating with shift of the cortex on opening were the presence of edema and depth of the tumor below skin surface; the predictors of shift at depth were the presence of edema, the lesion volume, midline shift, and magnitude of shift of the cortex on opening.

Gumprecht H K[35] in 1999 showed the neuronavigation system was useful in 125 neurosurgical cases out of 131 cases, with a target-localizing accuracy of 4 ± 1.4 mm (mean ± standard deviation).

Wirtz CR et al.[36] in 2000 used neuronavigation for primary glioblastoma. For each of 52 patients operated with neuronavigation, a patient operated on without navigation was matched and the completeness of tumor resection, including volumetric analysis, was examined by early post-operative MRI. Operating times were identical in the two groups, while preparation times were 30.4 min longer with navigation. Radiological radicality was achieved in 31% of navigation cases vs. 19% in conventional operations. The absolute and relative residual tumor volumes were significantly lower with neuronavigation. The authors concluded that neuronavigation increases radicality in glioblastoma resection without prolonging operating time and to tackle the problem of brain shift, neuronavigation should be optimized by intraoperative real-time imaging.

Ganslandt et al.[2] in 2002 showed their experience of neuronavigation assisted neurosurgical interventions in 432 patients using either the pointer-based or microscope-based navigational systems. The procedures included stereotactic biopsy, stereotactic cyst puncture/ventricular drainage, eloquent cortex/ tumor localization to facilitate tumor resection, assessment of neurovascular structures in the vicinity of tumors of the sellar-suprasellar regions, skull base, posterior fossa and ventricular region, and, surgery for epilepsy. The simultaneous use of intraoperative MRI to look for the remaining tumor was done in 159 patients. The mean system accuracy obtained by using both the fiducial registration as well as anatomical landmark-surface fitting computer algorithm was 1.81 mm.

Conclusion:

The best navigation during surgery is the anatomical knowledge mastered by the surgeon and his ability to visualize the distortion of the anatomy. Neuronavigation system is only an adjunct for the surgeon as well as for the patient to achieve maximum benefit with minimal complications. In the context of developing nations like Bangladesh, taking the economic aspects into consideration, operation theatres based on shared-resources concept, such as the AMIGO design, can be adapted in multidisciplinary centers where image-guided neurosurgery can be carried out and the limited resources expanded to an interdisciplinary suite to serve other different specialties.

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