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Neuro-navigation: Equipment, Tips, and Tricks on Brain Navigated Surgery

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Abstract

Neuronavigation is a system composed of advanced intraoperative equipment where a virtual link is created between digital images and anatomical structures such that intra-axial lesions are precisely located and removed safely and efficiently. Thus, neuronavigation has enormously increased the success rate of brain and spinal cord surgery compared to the era in which it did not exist. This article takes a look at and emphasizes, as a reminder, the benefits of neuronavigation, equipment used, equipment setup, tips and tricks on preoperative preparation of patients' images, and future perspectives on neuronavigation and equipment, aspects that are very rare in literature. A commonly used neuronavigation system is described, with regard to its parts, setup, instructions, and tips and tricks. This narrative review allows the reader to grasp the main aspects of neuronavigation, the functions of all the aspects, and what to expect during brain surgery. Although training with neuronavigation is a given in most developed parts of the world, in underdeveloped and developing countries the lack of equipment does not allow most neurosurgeons to have a first-hand experience. This article has aimed to ease the learning curve for neurosurgeons that are unfamiliar with neuronavigation.

Keywords
- neuronavigation
- benefits
- equipment
- tips and tricks
- future perspectives

Introduction

Advances and innovation in neuroimaging, surgical techniques, and medical equipment over the last decade have given an enormous boost to the improvement and success of contemporary neurosurgery. One of these advances has been image-guided neurosurgery, which is any method that uses imaging technology to promote the successful performance of brain and spine surgery.[1]

Roentgen's discovery and transformation of X-ray technology in the 1890s led to image-guided surgical procedures,[1,2] the importance of which was reinforced in the 1970s with the development of computed tomography (CT) and frame-based stereotaxy.[3,4] A microscope embedded with a frameless stereotactic positioning system was introduced by Roberts in 1986.[5]

The frameless neuronavigation system aims for a simultaneous virtual link between preoperative radiological images and real anatomical structures on the patient.[6] Three

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main components make up the technical features, namely the following:

- The patient's preoperative CT scan or magnetic resonance images (MRI) supply the raw data for the image generation software.
- The optical system, which determines the position of a pointer device and patient in the operating room by using a camera to track the positions of optical markers, affixed to them. The markers are attached directly to the pointer device or a *dynamic reference frame* connected to a support mechanism secured to the patient or very close to the patient.
- The *image processing system* is a *computer workstation* that allows for data storage and 3D reconstruction. Triplanar 2D images in axial, sagittal, and coronal planes, as well as 3D reconstruction images, provide a real-time dynamical display on a monitor screen.

With the help of an optically linked pointer, the landmarks on the patient are synchronized with the same structures obtained from the radiological images allowing for synchronization of the 3D model. The coordinates of the external fiducials are then adjusted to the neuroradiological coordinates, establishing the correlation of the patient's head relative to the 3D digitizer. From this point on, the optically linked pointer is able to show an exact localization either in three perpendicular sectional 2D views or in a 3D reconstructed image.[7]

Benefits of Neuronavigation

Apart from the operative microscope introduced by Yasargil in the 1960s,[8,9] neuronavigation has been of utmost benefit to neurosurgeons worldwide. Navigation systems such as the StealthStation Treon *Plus* have proven to be safe, effective, accurate, and assistive instruments to modern neurosurgery. This image-guided surgical modality supports and facilitates intraoperative orientation, making neurosurgical operations more precise and less traumatic, resulting in minimal brain damage and hence completing the goal of maximal safe resection.

The following are the benefits of neuronavigated brain surgery:

- Accurate localization on the surface of the skull is realized and procedures such as craniotomy can be tailored per patient for an exact and appropriate dimension.
- When performing skull base surgery, the accurate orientation of fixed bony structures by neuronavigation allows for precise orientation.
- Neuronavigation allows for precise intradural guidance through the demonstration of sulci, gyri, or cisterns in cases of deep-seated intra-axial lesions. Without neuronavigation, deep-seated intra-axial lesions will have to be "searched" for during surgery, as they are usually encased in the normal brain, thereby subjecting it to potentially fatal traumatic injury and damage (►**Fig. 1**).
- Neuronavigation allows for percutaneous puncture and biopsy without the need for screwed ring fixation as in a stereotaxy frame.
- Via neuronavigation, the surgeon is able to go through a repetitive "virtual walk" of the region of interest, providing invaluable visualization of the patient-based anatomy. The 3D representation provides clues to the exact location of the lesion along with neighboring eloquent structures. Thereafter, prospective surgical interventions can be simulated and a tailored approach suitable for the lesion can be determined. Consequently, neuronavigational systems are an excellent tool for presurgical planning and neurosurgical training.[7,10]
- The aim of image-guided neurosurgery has been lately to incorporate anatomical image data and functional information. Positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) data seem to be promising for this goal. PET is able to demonstrate the pathological area, especially in gliomas with the injected tracer but is insufficient in providing precise anatomical localization. fMRI adds information regarding eloquent brain areas.[2,11–14] The integration of this information into presurgical planning has led to refined strategies of resection and may facilitate more extensive resection near eloquent brain areas.
- Utilization of neuronavigation via 3D visualization of the vital tracts during brain tumor surgery has been reported[15] and may aid in the salvage of this tract during surgery.
- During epilepsy surgery, specifically for foci that are detectable by electroencephalogram (EEG) only, intraoperative or chronic extraoperative electrocorticography is essential for resection. The electrocorticographic mapping data can be integrated into the neuronavigation system allowing for visualization at the operative site. It can be used to determine the extent of resection in selective amygdalohippocampectomy, whenever the epileptogenic cortex is not significantly altered with respect to color, texture, or consistency.[16]
- Ear, nose, and throat (ENT) and maxillofacial surgery is able to benefit from neuronavigation as well. Both endonasal sinus and skull base surgeries pose a risk for the damage of vascular and neural structures in a confined space. Moreover, due to the destructive nature of diseases and previous procedures, surgical landmarks may be lacking. This limited intraoperative orientation during such procedures implicates a definite risk for complications. Neuronavigation is a beneficial tool for surgery of the anterior, middle, and posterior skull base, fossa infratemporalis, retromaxillary space, and paranasal sinuses. It has also proven to be effective during surgeries involving the upper neck and upper mediastinal approaches.[17,18]

Computer-aided technology was primarily developed for neurosurgeons for accurate guidance during neurosurgical operations, but nowadays neuronavigation has become an interdisciplinary tool. With studies proving its benefits in cranial surgery, promising studies have evaluated its

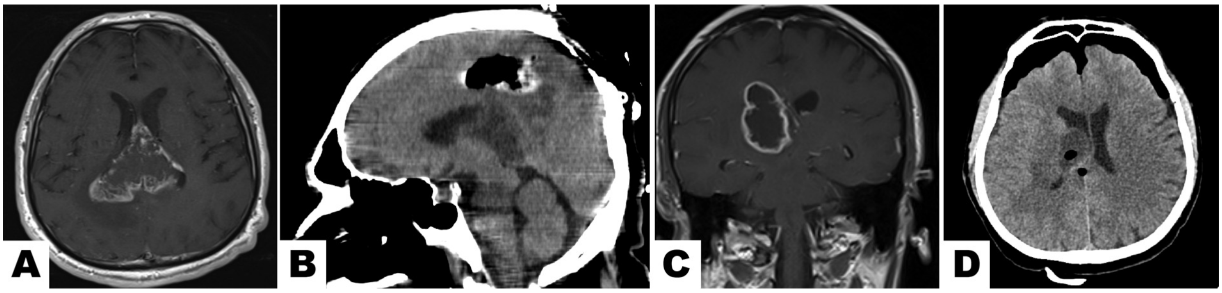

Fig. 1 (**A**) A 66-year-old male patient with a butterfly tumor. (**B**) Neuronavigation was not used and the follow-up control computed tomography (CT) showed that the lesion was direly missed. (**C**) A 60-year-old male patient with a deep-seated lesion. (**D**) Neuronavigation-assisted biopsy was successfully performed.

applicability in spinal surgery as well.[11,12,19] Aside from the clinical benefits, neuronavigation is an invaluable tool for training of young surgeons, allowing for a thorough understanding of the complex anatomy and appropriate surgical steps.

The Equipment

All neuronavigation systems have, basically, the same principle of operation. Each system is usually a hardware platform that enables real-time surgical navigation using radiological patient images. The software's primary aim is to render the patient's radiological images into a variety of perspectives (axial, sagittal, coronal, and oblique) allowing for rotation, zoom, and slicing. Although different systems may request specific unique details, slices thinner than 1 mm and inclusion of scalp landmarks (nose, ear, and eyes) are prerequisites for radiological images. The patient must remain completely still, especially during MR imaging as the distortion would decrease the accuracy of intraoperative targeting. The surgeon can manipulate the 3D model in order to simulate a trajectory. The number of 3D models can be increased to aid visualization of the lesion allowing for a rehearsal of the surgery. During the operation, the system is able to track the position of the instruments or a pointer while simultaneously portraying the position in regard to the radiological images.[20] This is the main core of **navigation** as the system is able to portray the exact position of the tip of a pointing device after the patient has been registered on a translation map. The **translation map** is created before the surgical incision, after the patient has been positioned. The external anatomical structures are used to register the points on the 3D render and thereafter the system displays within multiple patient image planes and other anatomical renderings.[20]

For simplicity, the equipment described here shall be the StealthStation Treon *Plus*, otherwise referred to as the Treon Treatment Guidance System (TTGS). This system is essentially made up of two separate but complementary carts: the **Viewing Cart** and the **Nav Cart**. The carts can be docked together or used separately, depending on the preference of the surgeon or the operating room setup. The viewing cart should be in a clear view of the surgeon and the Nav Cart should be in the sight of the patient to allow for precise and simultaneous navigation. **The Viewing Cart** contains the power supply, computer, and all related peripheral devices (►**Fig. 2**). The Viewing Cart can be used as a standalone surgical planning station and has a touchscreen monitor.

The touchscreen monitor is a high-resolution and flat-panel computer screen. When placed in the surgical field, it allows the physician to control the system without the need for an assistant, keyboard, or mouse, using a sterilized stylus. For any software fields that require text entry, a virtual keyboard appears onscreen with buttons that can be touched like a typewriter. Although the touchscreen eliminates the need for a keyboard and mouse, a **keyboard and mouse** may be utilized in certain circumstances.

Breakout Box

The Breakout Box acts as a junction box for various hardware devices, such as footswitch, reference frame, and probes. The breakout box does not contain any user-serviceable parts and can be hooked onto the operating room bed rail or the Nav Cart. During transportation and storage, the breakout box can be attached to the lower right-hand side of the Nav Cart.

The Nav Cart and Optical System

The Nav Cart (►**Fig. 3**) acts as the base for the camera and contains the **Tool Interface Unit** (**TIU)** and a storage drawer. The Nav Cart is connected to the Viewing cart via a communication cable, which also supplies the necessary power for the camera and the TIU. The **optical system** determines the position of an instrument (such as a probe of a pointing device) and the patient in the operating room by using a camera to track the positions of **optical markers** affixed to them. In the case of instruments, the markers are attached directly to the instrument being used while the optical makers on the dynamic reference frame (►**Fig. 4**) allows for tracking of the patient's position. The dynamic reference frame is securely connected to a mechanism to avoid any deviation throughout surgery.

There are two types of optical markers. Some components may have light-emitting diode (LED) optical markers, and others may have sterile spheres. LEDs generate and emit infrared light. Sterile spheres reflect infrared light that is emitted by the camera.

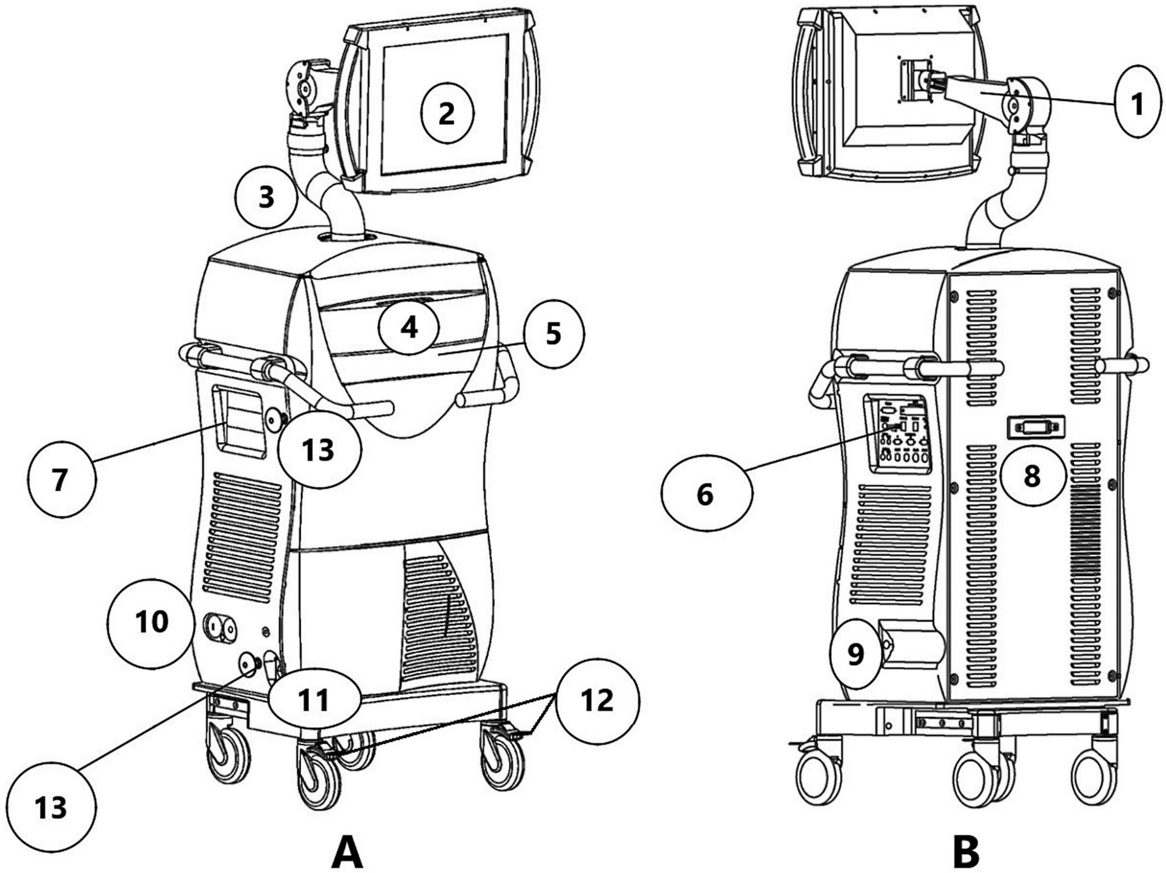

Fig. 2 The viewing cart exterior (**A**) front and (**B**) back views. (1) Articulating arm; (2) touchscreen; (3) chicane; (4) storage drawer; (5) keyboard/mouse drawer; (6) system side panel; (7) media bays; (8) cart docking mechanism; (9) cart communication cable connection; (10) On/off switch; (11) power cord outlet; (12) caster; (13) cable wraps.

The camera (sometimes called the localizer) detects the optical markers, determines their spatial positions using the principle of triangulation, and continuously reports this information to the computer. The computer uses this spatial information, in conjunction with information regarding the geometry of the instrument currently in use, to determine exactly where the tip of the instrument is located on the patient's anatomy. The system camera uses two lenses to geometrically triangulate the spatial coordinates of each optical marker on the instrument and reference frame. In the case of cabled devices (such as the active registration probe), the camera lenses receive infrared light signals directly from the LEDs on each device. In the case of passive (wireless) devices, the passive spheres on each device reflect light emitted by infrared illuminators on the camera back into the camera lenses. The camera continuously communicates the location of each LED or passive sphere to the system. In order to effectively detect the LEDs or passive spheres, the camera must be aimed toward the devices and positioned at the proper distance from them.

Dynamic Referencing

To maintain accuracy, the new generation of TTGS continuously tracks the position of the anatomy during registration and navigation. This is extremely vital as the patient's or the localizer's position may unintentionally be changed after the registration. Thus, the position of the dynamic reference frame should continuously be monitored to avoid inaccurate navigation.

This is unlike the first-generation TTGS, which had either system- or user-dependent intraoperative or application inaccuracy ranging from 0.5 to 6.5 mm.[7] The inaccuracy was due to inaccurate patient registration procedure on the one hand and brain shift (due to retraction with a spatula, working in the ventricles, or gravitational action due to the position of the patients' head) on the other hand. Thus, the new-generation TTGSs have an added advantage over previous-generation TTGSs due to dynamic referencing.

Setting up the Equipment

Certain precautions must be taken before setting up and starting the neuronavigation system. The system must be positioned at least 25 cm away from any source of flammable gas including anesthetic agents, oxygen, or nitrous oxide. For electrical safety reasons, any local area network (LAN) cables must be disconnected from the TTGS before proceeding with the system setup. Fluid must also be prevented from entering any part of the system. If fluid is suspected to have entered

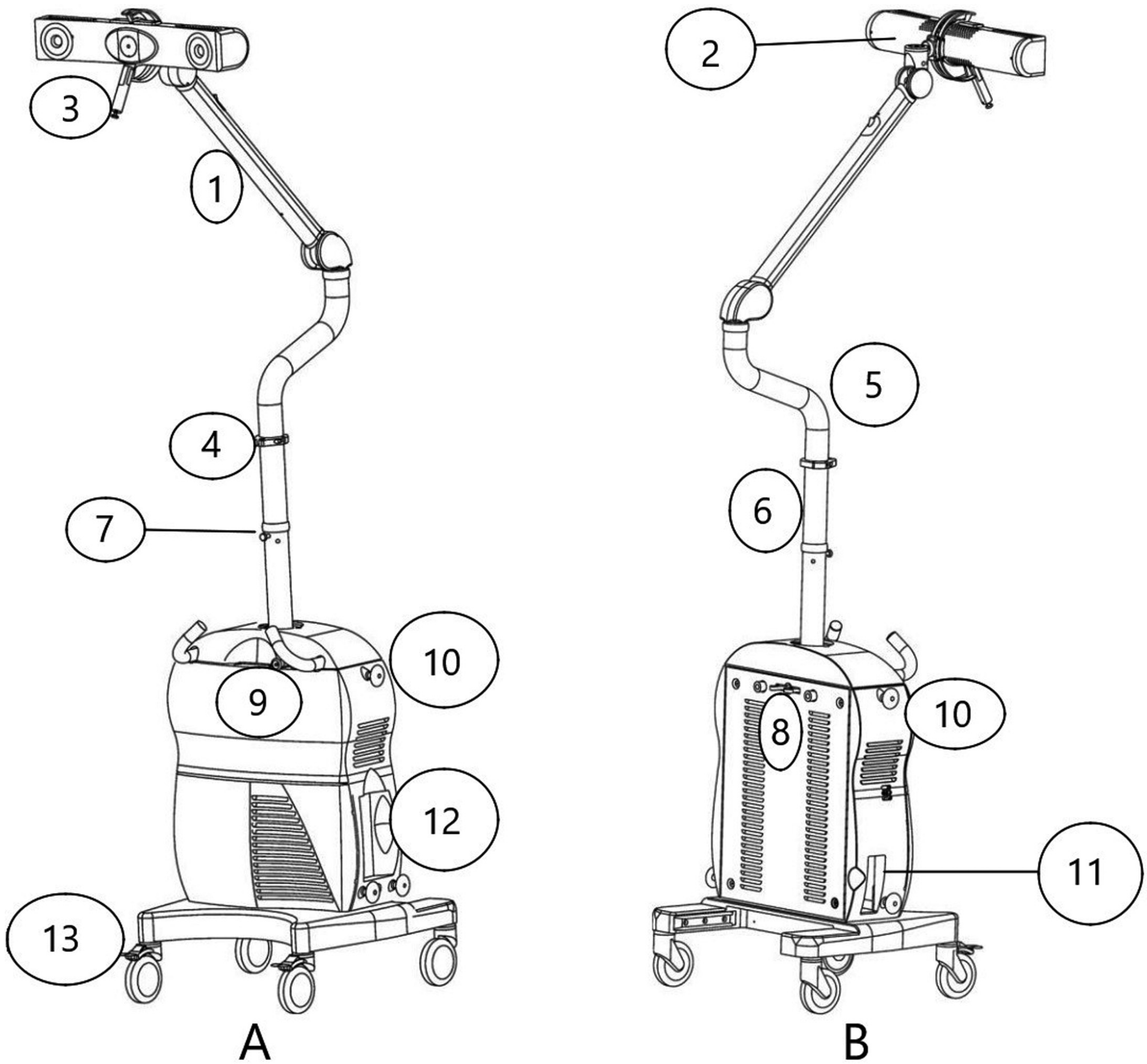

Fig. 3 The Nav Cart exterior (**A**) front and (**A**) back views. (1) Camera boom; (2) camera; (3) laser pointer; (4) camera docking port; (5) chicane; (6) post; (7) post lock; (8) cart docking mechanism; (9) storage drawer; (10) cable wraps; (11) cart communication cable; (12) breakout box; (13) caster locks.

any part of the unit, adequate dry time is allowed before connecting the system to power.

To Set Up and Start the System

1. The communication cable is connected from the Nav Cart to the Viewing Cart.
2. The system power cord is plugged into an electrical outlet.
3. The footswitch is connected to the **Button** port on the breakout box.
4. The green power on button on the left side of the Viewing Cart is pressed and briefly held down. The system would power up and the login screen would appear when all bootup diagnostics are completed.
5. The application icon is double-clicked to launch the software.

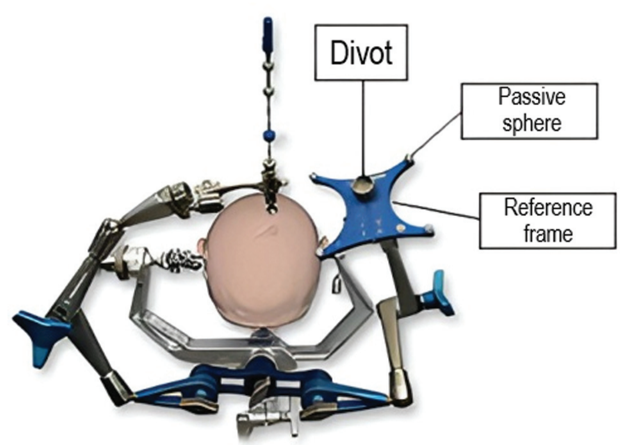

Fig. 4 Dynamic reference frame with passive spheres.

Docking the monitor is done by first adjusting (pushing down) the articulating arm such that the arm button is in the lock position. There will be an audible click when the arm locks. Second, the monitor arm is adjusted such that it is in the lock position. The lower elbow of the chicane would be at its closest point to the back of the system cart. Third, the monitor is rotated such that the face is pointing downward. Fourth, the monitor is pushed down toward the back of the cart.

The breakout box can hook onto the operating room bed rail or the Nav Cart. During transportation and storage, the breakout box is attached to the lower right-hand side of the Nav Cart. This is done by aligning the posts on the breakout box with the slots on the side of the cart and firmly pushing the posts into the slots.

Registration

Registration (to match the 3D position of the patient and the preoperative images) can be done using the following modalities:

- Tracer registration.
- Reg options.
- PointMerge.
- Touch-n-Go.

The TTGS tracer registration is always preferred as it gathers more points, does not require the use of fiducials, and has more flexibility (►**Fig. 5**). For first-generation navigation systems, it is important to ensure that the frame does not move with respect to the anatomy from the time of registration until navigation is complete because the position of the anatomy is defined by the position of the reference frame. Slippage or rotation of the reference frame concerning the anatomy after registration would result in inaccurate navigation. Fortunately, the newer-generation navigation systems do not have this problem due to dynamic referencing.

After the equipment is properly set up and the software launched, registration can begin by simply following the instructions on the touchscreen such as the following:

- Slice choice (of CT or MRI), of which 100 to 120 is often chosen.
- Navigation with Skin or Tumor, of which Skin is often chosen.
- Defining or circumscribing the tumor.
- Building the 3D image.
- Setting the point of Entry.
- Setting the Target (by clicking on the circumscribed brain lesion).
- Choice of pointing device, of which a small passive planner is often chosen.

Instruments designed for use with the TTGS have a precise instrument geometry and LED/sphere configuration. The specific geometry of each instrument is stored in a file to which the computer refers to determine where the tip of the instrument is located in relation to the instrument LEDs or spheres. Before commencing navigation, the user must inform the system in which instrument has been chosen, for example, the small passive planar. When the instrument to be used is selected from the probe list in the application software, *verification* must be done to ensure that the instrument chosen is not bent or otherwise damaged. This is done by placing the tip of the instrument into a metal divot on the reference frame and pressing the footswitch. The

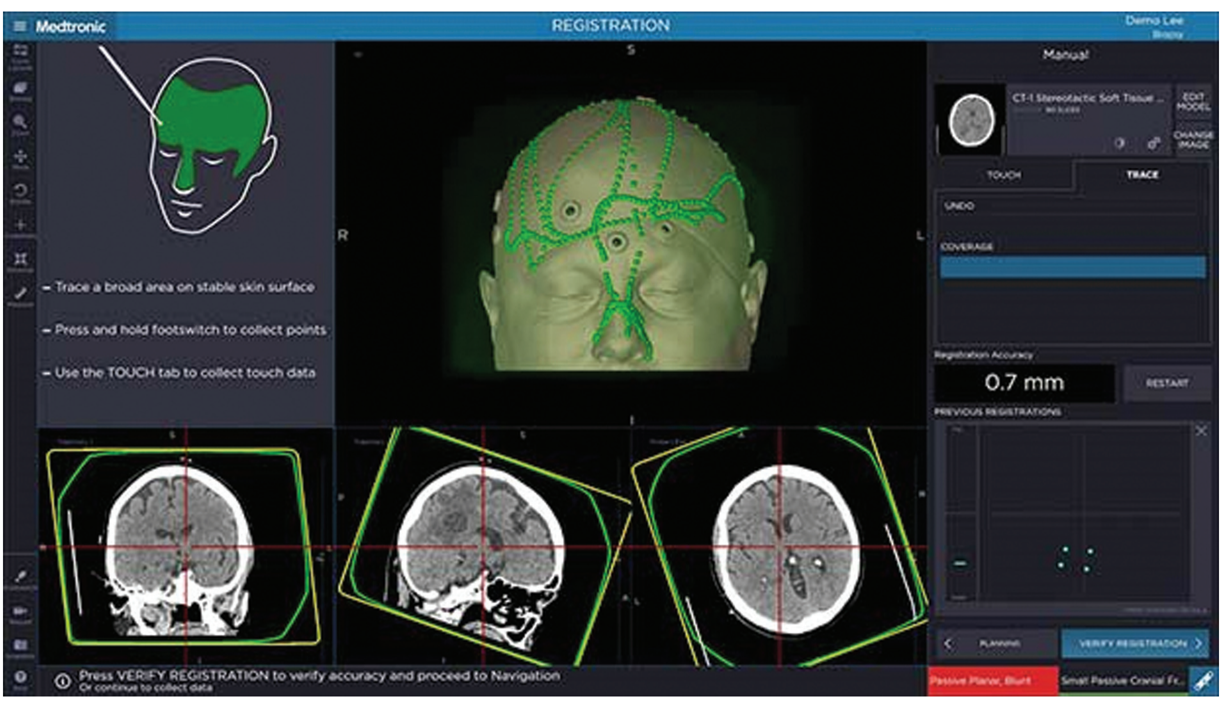

Fig. 5 Treon Treatment Guidance System (TTGS) screen during registration.

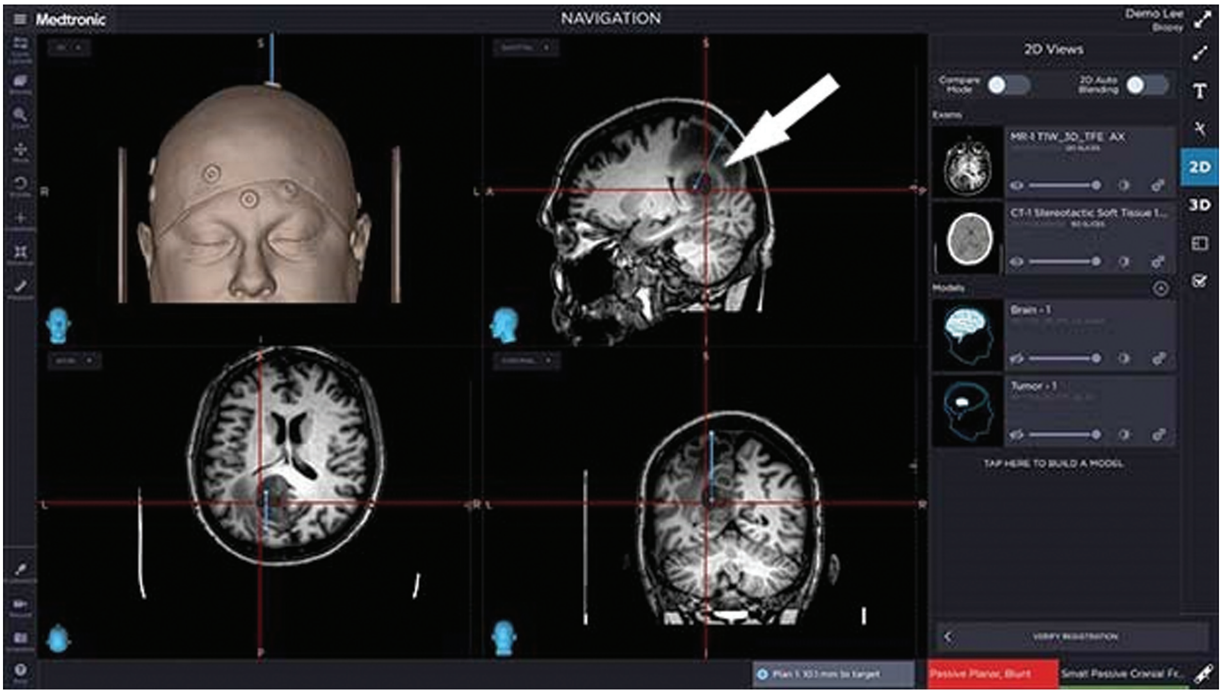

Fig. 6 Touchscreen of a neuronavigator showing a patient's brain images with a deep-seated lesion (*arrow*).

camera and computer then confirm that the instrument being used matches the specifications for the instrument selected in the software. The progress of registration would be displayed on the screen. After the pointing device is selected and verified, tracing is done on the patient for registration to be completed. When the navigation system is ready for use, the information would be displayed on the screen (►**Fig. 6**). The workflow of the neuronavigation system is summarized in ►**Fig. 7**.[21]

Tips and Tricks on Preoperative Patient Images Before Neuronavigation

Neuronavigation is multidisciplinary, involving neurosurgeons, ENT surgeons, neuroradiologists, biomedical engineers, etc. Preoperative images (CT or MRI) used for neuronavigation must have the following specifications (in collaboration with the neuroradiologist and radiologic technician) for effective use:

- The scan quality must be of high resolution.
- The slice thickness must be maximum 2 mm for CT and 1.5 mm for MRI. Minimum of 16-sliced CT and 1.5-T MRI are recommended.
- Specific prominent areas of the head and face such as the tip of the nose and tragus must be seen on the radiologic images. This is often done as a special request by the neurosurgeon to the radiology technician or neuroradiologist as these areas are used for careful and adequate registration.

Pitfalls

One of the most common pitfalls encountered while using neuronavigation in cranial surgeries is brain shift. This is a popular topic of investigation and continues to receive attention and research. Intraoperative brain deformation occurs almost in all cranial oncological surgeries as the brain parenchyma is distortable and dynamic. MRI is acquired in the anatomic supine position, whereas preoperative positioning of the patient and the head varies significantly. One way of overcoming this is acquiring the MRI in the planned surgical position of the patient where possible such as prone or park bench. In cases of further brain distortion due to active removal of malignant tissue, loss of cerebrospinal fluid (CSF) or shrinkage of healthy brain parenchyma, intraoperative ultrasonography (USG) may prove to be beneficial.[22,23] USG is an inexpensive and simple alternative to intraoperative real-time MRI. As USG images vary greatly and are distorted after surgical intervention, a baseline USG imaging should be obtained following durotomy.

Furthermore, most brain shifts occur in the gravitational direction; thus, a vertical view of the lesion by the surgeon would only cause a downward distortion that needs to be compensated for. Positioning the patient with this manner in mind would prevent a more complex 3D distortion. Avoiding diuretics and hyperventilation when possible is also another way to prevent or minimize the distortion. If the lesion is close to an eloquent area, the most critical area should be removed first before distortion. En bloc removal if possible is recommended and in the cases where piecemeal tactic is to be employed, placing large cotton patties in the resection cavity can help preserve preoperative dimensions of the lesion. Avoiding cyst puncture before total control over the boundaries of the lesion is also recommended.[22]

In order to compensate for intraoperative changes, solutions such as coherent point drift and fusion techniques

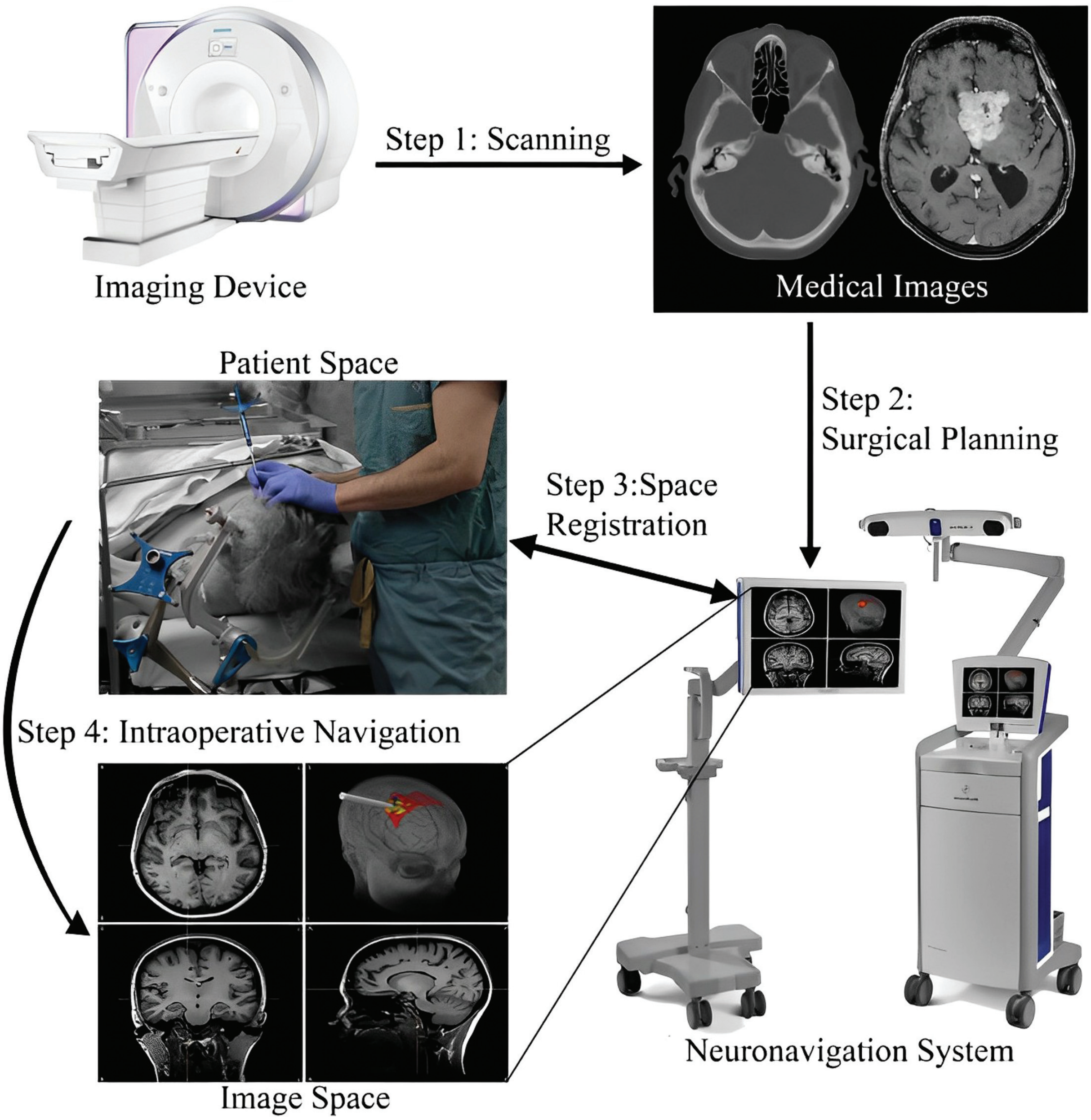

Fig. 7 Workflow of neuronavigation. The first step is acquiring the images, which are then uploaded to the system to allow for preoperative evaluation. This is followed by the registration of the patient via the use of the navigation probe and divots.[21]

have been advised. However, these solutions were unable to predict volumetric deformations and failed to register an accurate whole image from just visible landmarks and tissues.[22]

Neuroendoscopy

Neuronavigation-assisted endoscopy is gaining popularity with an increasing use. However, its necessity is debatable. Usage of endoscopy in hydrocephalus, cysts, and ventricular malignancies is replacing shunting and microneurosurgery. The employment of neuronavigation has been evaluated to be beneficial in over 50% of endoscopic surgeries.[24] However, it has not proved to be beneficial in endoscopic third ventriculostomy but rather essential for tumor biopsy or resection. It is also beneficial in defining the best trajectory even without the visualization of landmarks. Neuronavigation assistance has also aided in the detection of visually invisible subependymal tumors along with the basilary artery location beneath an opaque third ventricular floor.[24] A pitfall in using neuronavigation with endoscopes is the margin of error is much less compared to microsurgery. Thus, the positioning of the reference and navigation arrays on the navigated endoscope is of vital importance.[25] The classical random registration points used in neuronavigation may cause a great margin of error as neuroendoscopy addresses millimetric pathologies.

Future Perspectives

The benefits of contemporary neuronavigation in complicated brain, skull base, and spine surgery cannot be overemphasized. It is clear that small lesions in eloquent brain areas can be operated more radically with less morbidity compared to the preneuronavigation era. Therefore, manufacturers are urged to offer updated and specific systems for different applications. Workflow analyses and also cost–benefit evaluations have to be carried out to increase the efficiency of neuronavigation in the future. Apart from some initial work on evidence-based medicine, a sound basis for an assessment of neuronavigation from the perspective of health care system efficiency, effectiveness, and economy is required.[7]

Innovation in the medical equipment industry has led to the update of neuronavigation equipment such that the systems are now more user friendly, have dynamic referencing, and offer multiple tracking capabilities. The systems can also be integrated with external devices like microscopes, endoscopes, and ultrasound; a broad array of instrument offerings and core software applications for neurosurgery and spine procedures. In addition, modern neuronavigation systems are capable of interfacing with intraoperative imaging systems including intraoperative MRI (iMRI), intraoperative CT (iCT), C-arms, and O-arms to orient surgeons with 3D images of the patient's anatomy.

In addition to the foregoing capabilities of present-day neuronavigation systems, the ideal and desired future navigation system should adapt intraoperatively in an online fashion to the continuously changing anatomy (dynamic referencing) and possess automatic registration ability. The multidisciplinary aspect of neuronavigation has to be encouraged due to the rapidly evolving computer technology. Therefore, a continuous cooperation and exchange of information between clinicians, scientists, and medical equipment manufacturers have to occur to improve the systems for the benefit of the patients. Also, a common scientific language must be developed to create a global understanding not only for methods and techniques in the field of image-guided surgery but also for allowing adequate interdisciplinary communication.[1]

There is an ongoing development of new systems along with elaborating and improving present systems. In order to train new surgeons and primarily prepare surgeons for navigation-aided surgery, phantom models have been used. A stereotactic neuronavigation phantom with rigid or deformable parts would allow the surgeon before surgery to evaluate all aspects of entry point, patient and surgeon position, and parameters such as angle and depth.[26] This training method or preparation of the surgeon for surgery can also be improved by virtual reality (VR) training.[27] As the term "metaverse" is continuing to gain popularity, digital platforms providing a virtual world based on mostly visual cues may allow the surgeon to actually perform a surgery virtually while facing complications and difficulties that they may experience in the real scenario. This would also allow trainees to learn from their possible mistakes without harming any patient. The possibilities of VR training are endless, as this type of training has been used in the aviation field for decades.

Neuronavigation has also become a part of techniques and utilities used in complex pathologies that deemed impossible to treat surgically. Surgeons are finding unique ways to combine neuronavigation with other adjunct techniques to successfully operate on patients such as the removal of 2.3-cm midbrain pilocytic astrocytoma in a pediatric patient using tractography, neuronavigation, 3D exoscope, and a tubular retractor.[28] We believe further understanding of navigation will allow surgeons to create a "toolbox" of techniques and modalities to further improve the care for their patients.

Conclusion

The advantages of neuronavigation are enormous and well established. However, due to the cost, underdeveloped and developing parts of the world have limited access and experience. This review aimed to put forth a narrative guide to the use of neuronavigation, especially for surgeons with minimal or no access. The review also emphasized some key points and tips and tricks. It also aimed to provide evidence and framework for possible educational references at training institutions.

Authors' Contribution
All the authors contributed equally to this work

Conflict of Interest
None declared.

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