Chapter

Neuronavigation: Neuroimaging Applied to Neuromodulation and Neurosurgery

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Abstract

Neuronavigation has revolutionised neurosurgery by enabling precise targeting of brain structures through the integration of real-time surgical navigation and advanced neuroimaging (CT, magnetic resonance imaging (MRI), fMRI). Recent advances in infrared and electromagnetic technology have improved preoperative assessment, surgical planning and intraoperative guidance for procedures such as biopsies, tumour resections and deep brain stimulation (DBS). This chapter focuses on structural and functional neuroimaging modalities and their applications in surgical planning and execution. It also examines how neuronavigation contributes to neuromodulation techniques (DBS, transcranial magnetic stimulation (TMS)), tumour resection and epilepsy surgery. Emerging technologies such as resting-state fMRI and portable imaging systems for the operating theatre (POSITs) are discussed. The chapter concludes with an outlook on future developments, including the integration of artificial intelligence, machine learning and augmented/virtual reality to further improve accuracy and efficiency in neurosurgical practice. The continued integration of neuroimaging remains critical to optimising neurosurgical outcomes.

Keywords: neuronavigation, neuroimaging, neurosurgery, neuromodulation, deep brain stimulation, fMRI, tumour resection, epilepsy surgery

1. Introduction

The advent of neuronavigation has transformed neurosurgery, ushering in an era of unprecedented precision in navigating the intricate structures of the brain [1]. By integrating real-time surgical navigation with advanced neuroimaging technologies such as computed tomography (CT), magnetic resonance imaging (MRI) and functional MRI (fMRI), neuronavigation significantly minimises the risks associated with surgical procedures and improves patient outcomes [2, 3].

Recent advances in infrared and electromagnetic technology have further expanded the possibilities of neuronavigation [4, 5]. Compact, multifunctional electromagnetic navigation systems now enhance preoperative assessment, surgical planning, and intraoperative guidance. These innovations optimise procedures such as biopsies, tumour excision, and radiofrequency ablation, improving both precision and efficiency [6].

In the past, limited access to neuroimaging data during surgery posed a challenge and occasionally hindered important intraoperative decisions. In response, frameless stereotactic neurosurgery has evolved towards value-based image registration, overcoming the limitations of traditional feature detection algorithms [2, 3, 6, 7]. Innovative software platforms now enable better classification during surgical procedures and offer improved predictions of ablation zones and tissue necrosis assessments. As a result, neuronavigation supports the customisation of surgical procedures to the specific anatomical and pathological characteristics of each patient [3, 8].

In addition to tumour resection, neuronavigation plays a crucial role in a number of neurosurgical procedures, including deep brain stimulation (DBS) [1, 5, 9]. Modern methods include specialised tools that divide the planning phase into systematic steps and optimise access routes for the placement of electrodes. In many operating theatres today, advanced navigation systems are used for preoperative modelling and precise electrode placement, with cryogenically cooled electrodes providing even greater precision [1–9].

Given its growing number of applications, the continued prioritisation of neuroimaging in neuronavigation is essential. This chapter aims to provide a comprehensive overview of the principles, advances and future directions of neuronavigation in modern neurosurgery, with a particular focus on its application in neuromodulation and general neurosurgery.

1.1 Overview of neuronavigation

Neuronavigation represents a transformative technology in neurosurgery, enabling unprecedented accuracy through the integration of imaging techniques such as CT, MRI, and fMRI [2]. These modalities enable targeted interventions for a range of neurological and psychiatric disorders, particularly in neuromodulation applications [3, 5].

The global neurosurgical community increasingly relies on neuronavigation for intraoperative guidance, enhancing surgical precision and decision-making confidence [1, 3, 5, 8]. Traditional CT imaging has evolved to support real-time preoperative strategies, while MRI and resting-state fMRI provide complementary structural and functional insights, further augmenting neuronavigation's efficacy [10]. Modern MRI techniques offer multi-planar views with unparalleled clarity, empowering surgeons with comprehensive anatomical visualisation [11–16].

Despite its advancements, literature on the technological frameworks underpinning neuronavigation—such as CT control room configurations—remains limited. Expanding knowledge of patient-specific anatomy and neurovascular landmarks is critical to improving surgical accuracy and minimising iatrogenic risks [2, 7, 17].

A critical component of neuronavigation is the computer workstation, which processes multimodal imaging data to generate real-time, dynamic representations of brain structures. This integration enables surgeons to navigate anatomical regions with unprecedented clarity. Additionally, portable operating room imaging systems (POSITs) enhance intraoperative imaging accessibility, incorporating cost functions and dose analysis models to autonomously compute hazard zones, target positions, and trajectory paths [18–20]. Innovations such as super-compact laser actuation systems further refine stereotactic neuronavigation, compensating for slight head deviations and enhancing surgical precision [21, 22]. Laser guidance technologies, coupled with photon detectors tracking head position in three-dimensional space, ensure real-time synchronisation of anatomical representations, advancing surgical

motility and accuracy [23]. These developments herald a new era in neurosurgery, characterised by unparalleled precision and improved patient outcomes.

1.1.1 Hardware and software components

A typical neuronavigation system consists of [24–26]:

- *Workstation:* the heart of the system, a powerful computing unit that processes neuroimaging data and displays navigation information in real time. Modern workstations are equipped with high-performance processors, large RAM capacity and special graphics cards to process large amounts of image data and 3D rendering. The most common operating systems are Windows or Linux with intuitive and customisable user interfaces. Specialised software enables preoperative planning, patient registration and intraoperative navigation.

- *Tracking system*: This component tracks the position of the surgical instruments and the patient in space. The most common systems include.

    - *Infrared (IR):* Infrared cameras detect the position of reflective (passive) or emitting (active) markers attached to the instruments and patient. IR systems offer high precision and fast tracking but are susceptible to visual obstructions.

    - *Electromagnetic (EM):* A magnetic field generated by a transmitter is used to track the position of sensors attached to the instruments. EM systems are less affected by visual obstructions compared to IR systems and allow a wider tracking range but can be affected by metallic interference.

- *User interface:* A high-resolution monitor displays neuroimaging (MRI, CT, PET), the position of the surgical instruments superimposed on the images and other relevant information (e.g. distances to the target and approach angle). Modern user interfaces are interactive and allow the surgeon to manipulate images, plan trajectories and visualise 3D information.

- *Surgical instruments:* Instruments specifically designed to be tracked by the navigation system. These may include probes, suction devices, electrodes for deep brain stimulation (DBS) and other procedure-specific instruments.

- *Surgical planning software:* Specialised software enables preoperative planning, patient registration and intraoperative navigation. Advanced features include multimodal image fusion, anatomical structure segmentation, surgical simulation and 3D visualisation. Examples of surgical planning software include:

    - *Brainlab Elements:* A comprehensive suite of software modules for various neurosurgical applications, including tumour surgery planning, DBS planning and spine surgery planning. It integrates with Brainlab's navigation systems and offers features such as automatic trajectory planning, 3D visualisation and surgical simulation.

    - *Medtronic StealthStation:* A surgical navigation system that includes preoperative planning software and intraoperative tracking. The StealthStation

software enables multimodal image fusion, anatomical segmentation and trajectory planning. The tracking system uses infrared cameras to precisely localise surgical instruments.

- *Other software:* Other surgical planning platforms include Surgical Theatre SNAP, Siemens syngo.via and Philips IntelliSpace Portal.

These components work together to increase surgical precision, improve patient outcomes and support complex neurosurgical procedures.

2. Neuroimaging techniques

Neuroimaging has revolutionised modern neurosurgery and enables more precise interventions through better visualisation of brain structures and functions. Advanced imaging techniques have enabled surgical procedures previously thought impossible and improved both inpatient and outpatient outcomes [2, 3].

Structural imaging modalities such as MRI and 4D flow MRI provide critical insights into the architecture of the brain and cerebral blood supply and serve as a benchmark for pathology definitions and patient safety [11–14, 27, 28]. Functional imaging techniques such as fMRI and PET help to understand brain activity and inform surgical decisions. [10, 29–31]

The integration of these imaging modalities enables neurosurgeons to develop comprehensive preoperative strategies that ensure safer and more effective surgical interventions. In addition, real-time imaging enhancements, such as 3D visualisations and film loops, provide dynamic representations of blood flow and neural networks that further improve surgical precision.

2.1 Structural imaging

Accurate neurosurgical planning requires detailed anatomical maps tailored to each patient's unique brain structure. In the past, structural imaging modalities provided relatively low-resolution images. However, recent advances in imaging technology have significantly improved resolution and expanded their clinical applications [7, 32].

Modern MRI and CT techniques utilise a variety of imaging parameters, including T1/T2 relaxation times, diffusion coefficients and angiogenesis markers, to produce a highly detailed representation of brain anatomy. While MRI is known for its superior contrast resolution [33], CT remains indispensable due to its accessibility and fast acquisition times, especially in emergency situations where timely intervention is critical.

The integration of high-resolution imaging data into neuronavigation systems has significantly improved diagnostic accuracy and surgical precision. Nevertheless, it remains a challenge to achieve sub-millimetre accuracy in complex procedures. Overcoming these limitations requires constant innovation in imaging technology and the expertise of experienced radiologists to effectively interpret high-resolution data sets [1].

2.2 Functional imaging

Functional imaging techniques have become indispensable in modern neurosurgery. They provide insights into brain activity and facilitate the identification of critical functional areas prior to surgical interventions [35]. Among the most widely

used modalities are fMRI and PET, both of which provide valuable information about brain function and metabolic processes.

fMRI utilises blood oxygenation level-dependent contrast (BOLD) to measure changes in cerebral blood flow associated with neuronal activity. This non-invasive technique allows neurosurgeons to image functional areas of the brain, such as language and motor regions, improving preoperative planning and minimising the risk of postoperative deficits [7, 10, 33–34]. In addition, resting-state fMRI has proven to be a powerful tool for assessing functional connectivity within brain networks, providing further information on surgical strategies.

Resting-state fMRI (rs-fMRI) has proven to be a valuable tool for identifying intrinsic connectivity networks in the brain and provides unique insights into functional organisation [36]. In contrast to task-based fMRI, rs-fMRI measures brain activity in the resting state, revealing patterns of correlated activity between different brain regions. This is particularly beneficial in identifying eloquent areas and assessing the impact of lesions on brain networks, which can aid in surgical planning and risk assessment [37–38].

PET imaging, on the other hand, provides insights into metabolic activity through the detection of radiolabelled tracers that bind to specific biological targets. This method is particularly useful in identifying tumour characteristics and distinguishing between different tumour types, as well as in assessing brain metabolism in neurodegenerative diseases [39]. In combination with structural imaging techniques, PET can provide a comprehensive understanding of both the anatomical and functional aspects of brain pathology [40].

The integration of functional imaging into neuronavigation systems has significantly improved surgical precision by enabling real-time visualisation of critical functional areas during surgery. However, standardisation of protocols and interpretation of complex data sets remain a challenge. Continued advances in imaging technologies and analysis methods will be critical to optimising the benefits of functional imaging in neurosurgery.

3. Applications in neuromodulation

Neuromodulation techniques such as deep brain stimulation (DBS) and transcranial magnetic stimulation (TMS) have proven to be promising approaches for the treatment of a range of neurological and psychiatric disorders. Neuronavigation plays a crucial role in guiding and improving the precision of these interventions, thereby improving therapeutic outcomes.

In DBS, electrodes are implanted in specific regions of the brain to modulate neural circuits [41, 42]. Neuronavigation is essential for the precise placement of the electrodes. It ensures that the targeted brain structures are reached precisely while minimising the risk of damage to the surrounding tissue [43, 44]. Preoperative planning with MRI and CT imaging combined with intraoperative guidance by neuronavigation systems allows neurosurgeons to navigate the complex anatomy of the brain and place the electrodes with sub-millimetre accuracy.

Transcranial magnetic stimulation is a non-invasive neuromodulation technique in which magnetic pulses are used to stimulate or inhibit neuronal activity in specific regions of the brain [45]. Neuronavigation is used to direct the TMS coil to the desired cortical area, which enables precise and reproducible stimulation [46]. TMS controlled by neuronavigation has proven promising in the treatment of depression, obsessive-compulsive disorder and chronic pain, among others.

The integration of neuronavigation into neuromodulation techniques has revolutionised the treatment of neurological and psychiatric disorders, providing physicians with more precise and effective tools. Recent studies have highlighted the role of neuroplasticity in neuromodulatory interventions, highlighting how TMS and DBS can induce long-term synaptic changes in motor and cognitive networks [47–49].

For example, TMS-induced modulation of the prefrontal cortex has been associated with improved executive function and emotion regulation in both clinical and ageing populations, underscoring the importance of individualising stimulation protocols based on patient-specific functional connectivity profiles networks [47–49]. However, the optimisation of stimulation parameters and the personalisation of treatment strategies remains a challenge [46]. Further research and technological advances are needed to further improve the efficacy and safety of neuromodulation interventions (**Figure 1**).

3.1 Deep brain stimulation

DBS represents an advanced neuromodulation method that successfully addresses a variety of neurological conditions resistant to medication, including Parkinson's disease, epilepsy, OCD, chronic pain, and Tourette's syndrome. As an illustration of this, one can analyse what DBS has accomplished, which involves inserting and positioning fine wires and electrodes in precisely defined areas of the brain and subsequent delivery of controlled electrical impulses with pinpoint accuracy [41, 42].

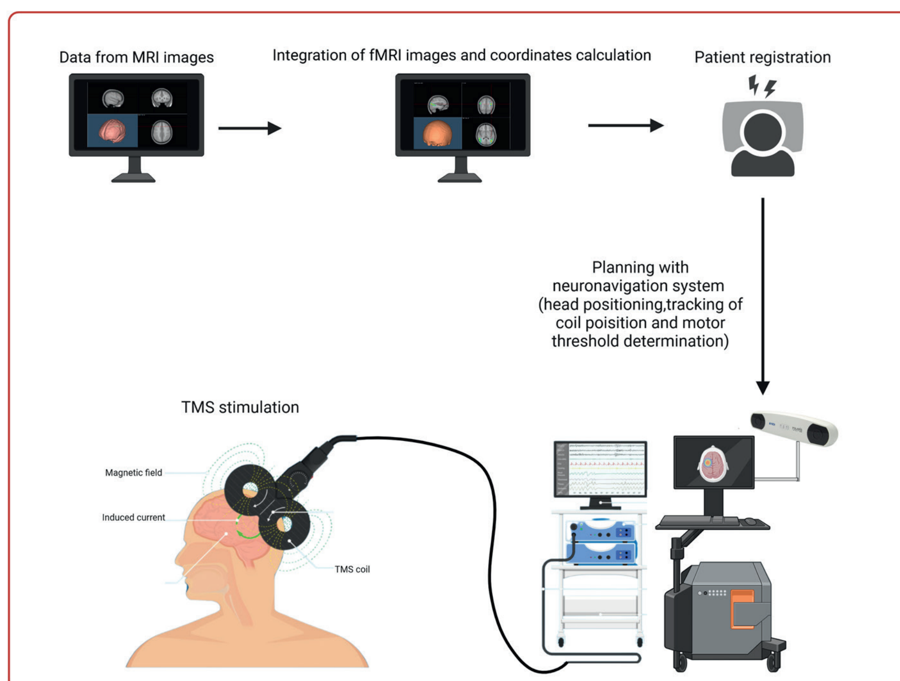

Figure 1.
Neuronavigation platform used in a transcranial magnetic stimulation (TMS) setting. The figure shows a complete neuronavigation setup for the precise localization of cortical targets during non-invasive neuromodulation treatments. This technology enables individualized stimulation based on the patient's anatomical features.

This process enables the adjustment of faulty electrical activity in the brain, resulting in symptomatic improvement.

By employing high-resolution neuroimaging techniques (like MRI or CT scans), this technology creates high-resolution anatomical maps of brain areas to allow for accurate localisation of targets in the brain [9, 43, 44]. Mapping in the preoperative phase makes it possible for neurosurgeons to select optimal electrode insertion sites on movement areas of the brain, particularly in the subthalamic region (STN), which is crucial for the regulation of motor functions [9, 50, 51].

The accuracy offered by neuronavigation enhances the chance of achieving clinical targets while lowering the risk of procedural complications by using real-time imaging. By preventing intraoperative complications such as hematomas and air intrusions, this capability plays a crucial role in enhancing patient safety [43, 44].

Notwithstanding the accomplishments of DBS, individual patient variability means that stimulation parameters often require modification postoperatively. Neuronavigation helps doctors to carefully track and adjust these parameters in real time according to the patient's changing responses, leading to personalised treatment and reduced toxicity. Moreover, advances in the standardisation of these modifications will ultimately provide a better opportunity for personalised care and increase the longevity and effectiveness of DBS.

3.2 Transcranial magnetic stimulation

Neuronavigation improves the efficacy and accuracy of transcranial magnetic stimulation (TMS), a non-invasive neuromodulation technique that uses magnetic fields to stimulate specific regions of the brain [46, 52]. TMS was developed in the 1990s and has been shown to be highly beneficial for mental health and various neurological disorders [45, 46]. Unlike invasive surgical procedures such as DBS, where electrodes are implanted to deliver electrical current, TMS therapy is performed on an outpatient basis, making it a less invasive alternative [45, 46]. Neuronavigation is critical to ensure that the TMS pulses are delivered precisely to the desired cortical target.

TMS exerts its therapeutic effect by repeatedly sending magnetic pulses to the scalp, thereby modulating electrical activity in the underlying brain regions. When directed to the motor cortex (precentral gyrus), it can elicit perceptible motor responses, demonstrating its potential for studying brain function. Neuronavigation improves the consistency and reliability of this targeting [53]. The integration of neuronavigation with repetitive TMS (rTMS) has significantly enhanced targeting accuracy, leading to improved treatment outcomes in neuropsychiatric disorders networks [47–49]. This is particularly evident in disorders such as major depression, where precise dorsolateral prefrontal cortex stimulation has shown higher response rates compared to non-navigated approaches. Additionally, the use of functional neuroimaging to personalise coil positioning has further refined stimulation strategies, optimising therapeutic efficacy while minimising variability.

Single-pulse TMS is mainly used in research, while rTMS is favoured in therapy to achieve long-lasting changes in brain activity with longer series of pulses. Low-frequency rTMS (1 Hz) suppresses activity, while high-frequency rTMS (≥ 5 Hz) has an excitatory effect [54]. Neuronavigation improves the precision of target localisation in rTMS, which translates into better treatment outcomes for various conditions. In medical areas where accuracy is critical — such as mood disorders, chronic pain, cognitive rehabilitation and stroke recovery — stimulating the relevant areas of the brain with neuronavigation can lead to more predictable outcomes [52, 54].

The FDA has approved rTMS for treatment-resistant major depressive disorder and is evaluating its use for obsessive-compulsive disorder [55–56]. Current studies are also investigating the efficacy of rTMS for neuropathic pain and stroke recovery. Intermittent theta burst stimulation (iTBS), a newer therapy, has received FDA approval. It is just as effective as rTMS but requires shorter session durations. Neuronavigation plays a crucial role in the accurate delivery of iTBS to the target region. While rTMS has shown promising potential, the heterogeneity of the results obtained in the different studies emphasises the need for refined treatment protocols, better identification of patients who could benefit from treatment and more convincing evidence of the efficacy of the therapy in different conditions. Neuronavigation helps to reduce this variability by improving targeting accuracy.

TMS offers a powerful non-invasive option for modulating brain function and serves as an alternative for patients who cannot undergo more invasive procedures such as DBS, especially with the help of neuronavigation technology.

3.3 MRI guided focussed ultrasound

Magnetic resonance-guided focussed ultrasound (MRgFUS) has become a rapidly advancing non-invasive method in neurosurgery that enables non-invasive thermal ablation of deep brain areas [56]. This technique, which enables non-invasive thermal ablation of deep brain areas, combines the accuracy of focussed ultrasound energy with the accuracy of real-time MRI imaging. MRgFUS is considered an acceptable alternative to conventional surgery as it is less invasive and allows localised treatment without surgical incisions. Similar to frameless stereotaxy in traditional neurosurgery, MRgFUS relies on accurate registration of the patient's anatomy in a preoperative image dataset [56].

By focussing ultrasound waves on specific regions of the brain, MRgFUS offers a promising new treatment method. MRI enables precise treatment planning and real-time monitoring, analogous to intraoperative imaging updates in open neuronavigation procedures. This real-time monitoring allows for better control of the treatment process and immediate adjustments based on tissue response. This is a key aspect of neuronavigation – adjusting the surgical strategy based on intraoperative feedback.

In addition, MR thermography, often in conjunction with ceramic cooling systems with disposable water buffers, allows for better thermal management during the procedure, reducing the likelihood of overheating and the resulting thermal effects.

Focussed ultrasound has been used to effectively ablate thalamic regions responsible for controlling tremors in patients with Parkinson's disease and Essential Tremor (ET) [57]. The FDA has approved MRgFUS for essential tremor (ET) to help patients for whom medical therapy has failed or who wish to avoid a more invasive surgical procedure.

Each patient is positioned in an MRI suite and wears a special helmet that directs the ultrasound beams to the target regions in the brain. This helmet and the MRI guidance system act as a form of non-invasive neuronavigation. In clinical practice, MRgFUS is increasingly being used for a growing range of neurological conditions, including the treatment of tremors in Parkinson's disease. The amount of tissue ablated is critical to the success of the procedure, and advanced imaging allows physicians to visualise the ablation in real time, providing important data on the effectiveness of the treatment. This real-time feedback loop is a hallmark of effective neuronavigation.

The thalamus is often the target of interventions to relieve symptoms, emphasising the need for immediate assessment of the impact of MRgFUS on tremor therapy [57].

Although the procedure is minimally invasive, patient selection is critical to its efficacy. Technical and non-technical factors such as facial twitching, head movements and sonication techniques can negatively impact treatment outcomes [57]. Advanced motion correction algorithms, like those used in neuronavigation, are being developed to mitigate the effects of these factors.

These models, combined with precise targeting and real-time feedback, are an example of the future of personalised, image-guided interventions that align with the core principles of neuronavigation.

4. Applications in neurosurgery

Neuronavigation has transformed neurosurgical interventions by enabling real-time visualisation of brain structures during procedures. This technology is particularly valuable in tumour resection, epilepsy surgery, and functional neurosurgery (**Figure 2**).

4.1 Tumour resection

Neuronavigation is changing tumour resection by moving from vague surgical approaches to precisely defined parameters that increase surgical readiness. Neurosurgeons equipped with neuronavigation can precisely define resection margins, maximising safe tumour removal while protecting surrounding

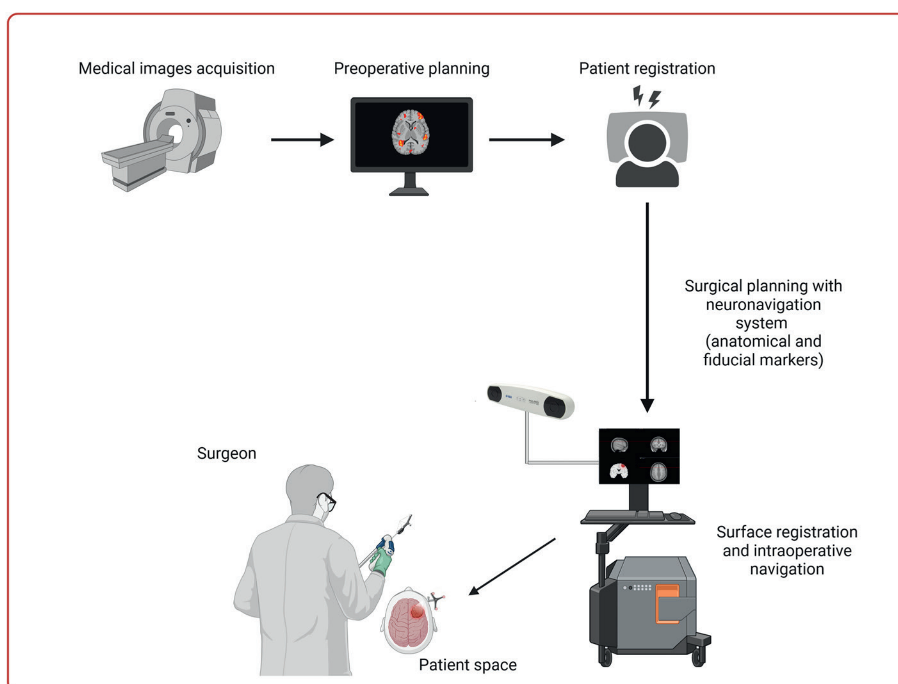

Figure 2.
Application of neuronavigation in a neurosurgical context. Operational view of a neuronavigation system used during a neurosurgical procedure. The platform provides real-time intraoperative visualization of brain structures, enhancing accuracy in tumor resection, epilepsy surgery, and functional neurosurgery.

healthy brain tissue responsible for neurocognitive function [1, 10, 33–34, 58]. Neuronavigation systems display real-time imaging data, allowing the surgical team to confirm complete tumour removal and adjust intraoperative strategies accordingly [59]. In addition, the introduction and implementation of advanced neuronavigation technologies has created enhanced spatial awareness of critical neuroanatomical regions — including key motor, sensory and language areas [58]. This enables minimally invasive surgical techniques while avoiding critical areas for speech or movement, even if these regions are near the tumour. The integration of state-of-the-art imaging techniques and neuronavigation improves the accuracy of the procedures performed by experts, increasing patient safety and treatment outcomes. By incorporating preoperative MRI and CT scans, neuronavigation systems offer real-time visualisation of the tumour's location and its relation to critical brain structures. This is particularly beneficial in cases involving tumours located near the eloquent cortex or deep within the brain [60–61]. The use of intraoperative imaging modalities, such as ultrasound and intraoperative MRI, further refines neuronavigation, allowing for real-time adjustments during surgery to ensure maximal safe resection. This leads to improved patient outcomes, reduced neurological deficits, and enhanced quality of life. The use of neuronavigation has improved the success and efficiency of surgical treatment, leading to higher rates of tumour control and fewer neurological complications. Despite these advances, challenges remain, particularly in addressing measurement inaccuracies associated with factors such as brain displacement, swelling, haemorrhage and patient movement. These factors can significantly affect the quality of imaging and the accuracy of navigation during complicated surgical procedures. Future advances in neuronavigation should focus on mitigating these inaccuracies to maximise the benefits of the technology. Improvements in surgical practise must prioritise patient outcomes by using state-of-the-art technologies to advance medicine and surgery. Continuous innovation in neuronavigation is critical to achieving these goals.

4.2 Epilepsy surgery

The increasing use of visual technology is now a cornerstone of the surgical treatment of epilepsy, as it makes the localisation and removal of the epileptogenic zone even more precise. A surgical strategy is not just another item on the treatment menu but is often the last resort for those patients whose seizures have not responded to multiple medications. With such complex surgical techniques, it is important to precisely define the location of the epileptic focus. The integration of these approaches with neuronavigation in the surgical planning phase should be considered standard practice [62]. In addition, frameless stereotactic neuronavigation improves the precision of localisation of the epileptogenic focus [63].

The CyberKnife system, for example, is a state-of-the-art robotic radiosurgery platform that combines CT and MRI information to precisely deliver ionising radiation to brain lesions [63]. The principles of neuronavigation are crucial for the precise targeting of these lesions with CyberKnife. This targeted procedure offers a non-invasive alternative to conventional surgery. By improving visualisation and planning capabilities, these advanced techniques optimise the effectiveness and safety of epilepsy surgery, allowing surgeons to precisely locate seizure foci while reducing damage to critical brain regions [63].

DOI: http://dx.doi.org/10.5772/intechopen.1010245

5. Usage protocols

The effective use of neuronavigation requires a precisely defined protocol:

- *Image acquisition*: neuroimaging (MRI, CT, PET) is performed according to specific protocols for the surgical procedure. It is crucial to minimise artefacts and obtain high quality images.

- *Preoperative planning*: Using neuronavigation software, the surgeon defines the surgical target, the access routes and the structures to be avoided. Planning can include segmentation of tumours, definition of brain nuclei for DBS or mapping of eloquent areas using fMRI.

- *Patient registration*: Registration matches the space of the preoperative images with the physical space of the patient. This can be done as follows:

- *Anatomical landmarks*: Identification of anatomical points that are easily recognisable both on the images and on the patient (e.g. the outer canthus of the eye and the root of the nose).

- *Fiducial markers*: Radiopaque markers are applied to the patient's head before the image is taken. These markers are easily recognisable both on the images and during registration.

- *Surface registration*: Use of a scanner or probe to capture a point cloud on the surface of the patient's head, which is then compared with a surface reconstructed from the preoperative images.

- *Instrument calibration*: Surgical instruments are calibrated to determine their position relative to the tracking markers or sensors.

- *Intraoperative navigation*: During the procedure, the neuronavigation system displays the position of the instruments in real time on the preoperative images so that the surgeon can navigate precisely to the target.

- *Postoperative verification*: Postoperative images (CT and MRI) can be acquired to verify the correct positioning of the instruments or the extent of the resection.

5.1 Workflow for DBS

1. Preoperative planning:

   a. *Imaging:* High-resolution MRI (T1-weighted, T2-weighted) to visualise the target nuclei (e.g. the subthalamic nucleus and the globus pallidus internus). Sometimes a CT scan is also used to plan the transcranial approach.

   b. *Segmentation:* The target nuclei are segmented manually or automatically on the MRI images.

c. *Trajectory planning:* The electrode path is planned to avoid vascular and ventricular structures and to reach the target at an optimal angle. Specialised software is often used for DBS planning.

d. *Integration of fMRI* (if applicable): If the patient has undergone task-based fMRI to map motor or cognitive function, this data is integrated into the planning to avoid critical functional areas during electrode placement.

2. Surgical procedure:

a. *Registration*: The patient is registered with the neuronavigation system using fiducial markers or anatomical landmarks.

b. *Electrode implantation*: A small burr hole is created and the DBS electrode is advanced along the planned trajectory using the neuronavigation system for real-time guidance.

c. *Microelectrode recording* (optional): Microelectrode recording can be used to further refine electrode placement based on the characteristic electrophysiological activity of the target structure.

d. *Intraoperative stimulation* (optional): Intraoperative stimulation can be performed to assess the clinical effects and identify any side effects.

3. Postoperative verification:

a. *Imaging*: postoperative CT to verify the position of the electrode.

b. *Programming*: The electrode is programmed to ensure optimal stimulation and reduce side effects. Programming is an iterative process that requires long-term follow-up.

5.2 Workflow for TMS

1. Pretreatment planning:

a. *Imaging:* High-resolution, high-resolution T1-weighted MRI may be performed to provide an anatomical reference for target localisation. While not always mandatory, it significantly enhances the accuracy of the targeting process.

b. *Integration of fMRI* (if applicable): Functional MRI may be used to map cortical targets, utilising task-related activity and resting state connectivity. This is particularly useful for setting personalised treatment goals.

c. *Data loading:* The MRI and fMRI data are loaded into the neuronavigation system to facilitate target localisation.

d. *Coordinate calculation*: The neuronavigation system computes the coordinates, often utilising MNI or Talairach spaces, to pinpoint the target accurately.

2. Registration of the patient:

    a. *Patient positioning:* The patient is seated comfortably, and the TMS coil is positioned above their head.

    b. *Head registration:* The patient's head is registered using the MRI data. Anatomical landmarks such as the nasion, inion, and preauricular points are employed to align the head with the MRI model.

    c. *Surface matching:* A 3D camera scans the patient's head, and an infrared tracking system is used to match the scanned surface to the MRI model.

    d. *Tracking of coil position:* The neuronavigation system tracks both the position and orientation of the coil relative to the target throughout the procedure.

    e. *Motorised threshold determination:* TMS is only initiated after determining the resting motor threshold (rMT). The motor cortex is stimulated, typically in the hand area, to identify the minimal stimulus required to induce a visible muscle twitch in the contralateral hand. The rMT serves as the baseline for adjusting stimulation intensity in subsequent therapeutic sessions.

3. TMS stimulation:

    a. *Coil positioning:* The TMS coil is positioned over the identified target region, and its placement is monitored in real-time with the neuronavigation system to ensure optimal positioning.

    b. *Stimulation parameters:* The stimulation parameters, such as frequency, intensity (relative to rMT), pulse pattern, number of pulses, and interval between sessions, are set according to established protocols while considering individual patient characteristics.

    c. *Administration of pulses:* The neuronavigation system ensures the accuracy of the coil placement during each stimulation pulse, which is continuously maintained throughout the session.

4. Post-treatment verification:

    a. *Response monitoring:* The patient's response to the stimulation is continuously monitored throughout the session, with adjustments made to the coil's position and stimulation parameters as necessary to optimise the therapeutic effect and minimise discomfort.

    b. *Safety monitoring:* The scalp temperature is monitored to prevent overheating, and the patient is observed for any adverse effects during the procedure.

5.3 Workflow for tumour resection

1. Preoperative Planning:

    a. *Imaging*: MRI with and without contrast, DTI (Diffusion Tensor Imaging) to visualise the tumour and surrounding structures (eloquent areas, white matter tracts).

b. *Segmentation*: The tumour and critical structures are segmented on the MRI images.

c. *Integration of fMRI*: Task-based fMRI is used to identify and map eloquent areas (motor, sensory, language) near the tumour. This data is then integrated into the neuronavigation system to guide surgical planning and minimise the risk of postoperative deficits.

d. *Resection Planning*: The resection strategy is defined to maximise tumour removal and minimise the risk of neurological deficits.

2. Surgical Procedure:

a. *Registration*: The patient is registered to the neuronavigation system using fiducial markers or anatomical landmarks.

b. *Guidance during Resection*: During resection, the neuronavigation system displays the position of the surgical instruments relative to the tumour and critical structures, allowing the surgeon to navigate precisely.

c. *Intraoperative Imaging* (Optional): Intraoperative ultrasound or MRI can be used to evaluate the extent of resection in real time and to identify any residual tumour.

3. Postoperative Verification:

a. *Imaging*: Postoperative MRI to evaluate the extent of resection and identify any complications.

6. Challenges and future directions

Neuronavigation will continue to evolve through the integration of artificial intelligence (AI), machine learning (ML) and augmented/virtual reality (AR/VR) technologies [64]. These innovations have the potential to increase surgical precision, streamline workflows and improve patient outcomes. However, to fully realise the potential of these technologies, several challenges need to be overcome.

The integration of AI and ML algorithms into neuronavigation systems can facilitate real-time image analysis, predictive modelling and personalised surgical planning. AI-powered tools can automatically segment brain structures, identify critical functional areas and predict the optimal surgical approach based on the patient's individual anatomy and pathology. However, concerns regarding data privacy, algorithmic bias and regulatory approvals must be carefully considered.

AR/VR technologies offer new opportunities for surgical education, preoperative planning and intraoperative guidance [65]. AR overlays can provide surgeons with real-time information about the anatomy and function of the brain, improving spatial awareness and surgical precision [65]. VR simulations can allow surgeons to practise complex procedures in a safe and controlled environment, improving their surgical skills and reducing the risk of complications [65]. However, developing user-friendly interfaces and validating the effectiveness of these technologies in clinical practise is still a challenge.

Overcoming these challenges will require a collaborative effort between neurosurgeons, engineers, data scientists and regulators. The application of neuronavigation in neuromodulation extends beyond TMS and DBS, with growing interest in its role in real-time functional monitoring networks [47–49]. Evidence form recent studies suggest that combining neuronavigated neurostimulation with behavioural interventions could enhance cognitive and affective outcomes, paving the way for novel multimodal therapeutic strategies [47–49]. By embracing innovation while carefully considering the ethical and practical implications, we can realise the full potential of neuronavigation and transform neurosurgical care.

7. Conclusions

Neuronavigation has fundamentally reshaped modern neurosurgery, enabling more precise and less invasive interventions across a spectrum of neurological and psychiatric conditions. By integrating advanced neuroimaging techniques with real-time surgical navigation, neuronavigation enhances the accuracy of tumour resection, optimises electrode placement in neuromodulation procedures, and facilitates the identification of epileptogenic zones in epilepsy surgery.

The ongoing integration of artificial intelligence, machine learning, and augmented/virtual reality technologies holds immense promise for further advancing the field. These innovations have the potential to refine surgical planning, automate image analysis, and provide surgeons with immersive training and guidance. However, realising the full potential of these technologies requires addressing challenges related to data privacy, algorithmic bias, and standardisation of protocols.

Despite these challenges, the future of neuronavigation is bright. By fostering collaboration among neurosurgeons, engineers, data scientists, and regulatory agencies, we can continue to push the boundaries of what is possible and improve the lives of patients with neurological and psychiatric disorders.

Conflict of interest

The authors declare no conflict of interest.

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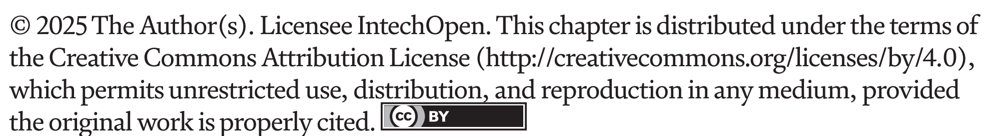

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