Scopes and Limitations of Image-Guided Neurosurgery: A Retrospective Study

DISSERTATION

Submitted to the University of Madras in

Partial fulfillment for the award of the degree of

MASTER OF SCIENCE

IN

NEUROSCIENCE

(Faculty of Medicine)

By

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May 2024

In the official Letter Head of the Guide

CERTIFICATE

This is to certify that this dissertation entitled "Scopes and Limitations of Image Guided Neurosurgery: A Retrospective study" submitted to the University of Madras in partial fulfillment of the requirements for the award of the degree of **MASTER OF SCIENCE in Neuroscience** of the University of Madras by Tiainla (Register No: 35922112), was based on a project executed under my guidance and supervision at Postgraduate Institute of Neurological Surgery , Dr Achantha Lakshmipathi Neurosurgical Center ,VHS Hospital and Research Center Taramani, Chennai – 600113. Tiainla actively participated and had contributed significantly during the period from August 2023 to May 2024.

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I, **Tiainla,** hereby declare that the dissertation entitled "**Scopes and Limitations of Image-Guided Neurosurgery: A Retrospective Study"** submitted by me, in partial fulfillment of the requirements for the award of the degree of Master of Science in Neuroscience of the University of Madras was based on a project work carried out under the supervision and guidance of **Dr Anil Pande, Adjunct Professor of Neurosurgery, Apollo Hospitals Education and Research Foundation, Sr. Consultant Neurosurgeon, Postgraduate Institute of Neurological Surgery. Dr Achantha Lakshmipathi Neurosurgical Center ,VHS Hospital and Research Center ,** during the period from August 2023 to May 2024.

I also declare that I was actively involved and had carried out the work assigned to me diligently and truthfully to the best of my knowledge and belief.

Date: Signature of the Candidate

CERTIFICATE

The dissertation entitled "SCOPES AND LIMITATIONS OF IMAGE-GUIDED NEUROSURGERY: A RETROSPECTIVE STUDY " was submitted by Tiainla for the degree of Master of Science – in Neuroscience (Faculty of Medicine) during the viva-voce examination conducted at Department of Anatomy, Dr. Arcot Lakshmanasamy Mudaliar PostGraduate Institute of Basic Medical Sciences, University of Madras, Taramani Campus, Chennai - 600113, India on 16th May, 2024.

Signatures of the Members of the Department Committee

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Abstract

Image-Guided Neurosurgery (IGNS) represents a significant advancement in the precision and safety of neurosurgical procedures. This thesis explores the scopes and limitations of IGNS through a comprehensive retrospective study, including surveys from practicing neurosurgeons and a thorough review of current literature. The findings highlight the transformative impact of IGNS on neurosurgery, particularly in enhancing surgical accuracy, reducing patient morbidity, and improving overall outcomes.

Key technological advancements, such as the integration of advanced imaging modalities (CT, MRI) and the development of sophisticated navigation systems, have greatly enhanced the capabilities of neurosurgeons. These technologies provide detailed anatomical and functional insights, enabling more precise targeting of lesions and minimizing damage to surrounding healthy tissues.

However, the study also identifies several challenges and limitations in the current state of IGNS. Technical issues such as brain shift and the need for real-time image updating pose significant challenges. Usability concerns, including the complexity of systems and high cognitive load on surgeons, are also critical barriers. Additionally, the high cost of IGNS technology and the need for extensive training limit its widespread adoption.

The thesis concludes with recommendations for future research and development to address these challenges. Enhancements in user interface design, real-time imaging capabilities, cost-effective solutions, comprehensive training programs, and system reliability are essential for advancing IGNS technology. By addressing these areas, the field can move towards more effective and widely accessible neurosurgical procedures, ultimately improving patient care and surgical outcomes.

Keywords:

Image-Guided Neurosurgery, IGNS, neurosurgery, brain shift, real-time imaging, navigation systems, surgical precision, technological advancements, usability, training programs, patient care.

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CHAPTER 1

1.1 Introduction

The history of neurosurgery is a testament to the relentless pursuit of precision and safety in the treatment of brain disorders. This medical field has evolved dramatically from its primitive beginnings, overcoming significant challenges to become the sophisticated discipline it is today. Beginning from the ancient times with Inca (1), Hippocrates and Galen, through the Renaissance and World Wars until recently, neurosurgical procedures have constantly been performed as it has always been talked about neurosurgery. H.Cushing , during the 1900s brought modern neurosurgery to the world (2) . Since then, neurosurgery has reached such levels of development that it may be considered to be one of the most futuristic specialties of all times. The early stages of neurosurgery was a perilous endeavor, primarily due to the lack of understanding of the brain's complex structure and functions. Early neurosurgeons operated without the guidance of detailed brain maps or imaging, relying heavily on surface anatomy and crude localization techniques. This era was characterized by high morbidity and mortality rates, as the precision required to safely navigate and operate on the brain was virtually unattainable.

The first-recorded use of an apparatus created to localize intracranial structures in humans was by Dr D.N Zernov, Surgeon and Professor of Anatomy at Moscow University, Russia, in 1889 which consisted of an aluminum frame fixed to the skull called the "encephalometer" and used superficial anatomic landmarks to predict surface brain topography (3). Further innovations came into play by Dr. V.H. Horsley, Professor of Clinical Surgery and Robert H. Clarke, Physiologist and Engineer, at University College London, England created the first stereotactic frame that used mathematical calculations based on cartesian coordinates. The application of stereotactic methods to human patients , however, took several more decades to develop, mainly due to the complexity of human brain anatomy and the need for more sophisticated imaging techniques. The turn of the 20th century marked the beginning of significant advancements, the development of the pneumoencephalogram, which involved replacing cerebrospinal fluid with air to visualize the brain's ventricles, provided some guidance for surgeons but was still crude and painful for patients. Then the introduction of the cerebral angiogram by Egas Moniz provided the first glimpses into the vascular architecture of the brain, offering neurosurgeons a rudimentary roadmap for surgery (4) . Despite this progress, the field was still hindered by a lack of tools to accurately identify and target deep brain structures.

The real revolution in neurosurgery began with the advent of neuroimaging technologies. The development of computed tomography (CT) in the 1970s followed by magnetic resonance imaging (MRI) in the 1980s, provided neurosurgeons with detained, three-dimensional views of the brain, transforming surgical planning and execution. These imaging modalities allowed for precise localization of lesions and critical brain structures significantly reducing the risks associated with surgery. In the late 20th and early 21st centuries, the development of frameless stereotactic systems and the integration of computer-assisted navigation technologies further revolutionized stereotactic neurosurgery which have allowed for more flexible, less invasive procedures and have broadened the range of conditions that can be treated stereotactically.

In the intricate realm of neurosurgery, where the margin for error is negligible, the advent of image-guided neurosurgery (IGNS) stands as a pivotal innovation, bringing forth a new era of precision and safety. Image-guided surgery can be defined as the quantitative use of preoperative images during surgery, or in other words using the spatial parameters of the preoperative images during surgery to provide guidance to the surgeon (5) . The exigency for precision is paramount in neurosurgery, given the intricate and delicate nature of the human brain and its surrounding structures. Traditional neurosurgical approaches, while groundbreaking in their time, have been fraught with challenges and limitations, primarily stemming from the inherent complexity of cerebral anatomy and the risks of collateral damage to critical neural pathways. The advent of advanced imaging-modalities such as computed tomography (CT) and magnetic resonance (MR) imaging brought about a shift in the direction of information flow, giving birth to frameless stereotaxy or interactive-image guided neurosurgery. This technique, integrating real-time imaging into surgical procedures, has significantly enhanced the neurosurgeon’s ability to navigate complex brain structures, minimize damage to healthy tissue, and improve patient outcomes. As this technology continues to evolve, its application scope expands, encompassing a wide range of neurosurgical interventions from tumor resections to vascular malformations and beyond. However, despite its transformative potential, image guided neurosurgery also encounters specific limitations and challenges that warrant thorough investigation.

1.2 PROBLEM STATEMENT

Neurosurgery is a field marked by intricate challenges, largely due to the complex and delicate nature of the human brain and central nervous system. Neurosurgeons must navigate an exceedingly dense network of critical structures, such as blood vessels, nerve fibers and functional regions, where even the slightest inaccuracy can lead to severe or catastrophic outcomes, including loss of function, severe neurological deficits or even fatality. The primary challenges that amplify the necessity for image-guided neurosurgery (IGNS) include the intricate brain anatomy with its critical structures tightly packed within a small space, the necessity for minimizing surgical trauma to preserve neurological function, and the inherent brain shift phenomena that occur during surgery.

Furthermore, the individual variability in brain anatomy complicates the application of a one-size-fits-all approach, necessitating highly customized surgical plans. Identifying and distinguishing pathological tissue from healthy tissue is another significant hurdle , especially when dealing with brain tumors where the demarcation is not always clear cut. This differentiation is critical not only for the effective removal of pathological tissue but also for ensuring the integrity of surrounding healthy tissue to maintain the patient's quality of life post-surgery.

The importance of precision and accuracy in neurosurgical practice cannot be overstated, given the high stakes of brain surgery. The challenges faced by neurosurgeons highlight the critical need for advanced imaging guidance technologies. The technologies enhance the surgeon's ability to plan, navigate and execute procedures with higher precision and real-time feedback, thereby significantly mitigating risks and improving surgical outcomes.

In light of these challenges, there is a pressing need for continued innovation and integration of image-guided systems in neurosurgery. Despite the advancements in imaging technologies, image-guided neurosurgery still faces challenges like technical limitations, accuracy issues, usability concerns and cognitive load. These factors not only hinders the effectiveness in real-time settings but also complicates surgical workflow. IGNS should deliver detailed anatomical and functional maps for surgical planning and provide real-time intraoperative imaging to account for brain shifts and other changes during surgery. There is further need to enhance the precision and accuracy of neurosurgical procedures, thereby improving patient safety and outcomes while minimizing the risk of postoperative complications and the necessity for additional surgeries.

1.2 OBJECTIVES

This thesis aims to explore the extensive scope of image guided neurosurgery, delving into its technological underpinnings, clinical applications and the significant impact it has had on the neurosurgical landscape. It seeks to highlight how advances in imaging modalities , such as MRI, CT scans and functional MRI, coupled with sophisticated software algorithms, have contributed to the refinement of surgical techniques, enabling surgeons to perform procedures with enhanced accuracy and confidence.

Simultaneously, this investigation critically examines the limitations and challenges associated with image guided neurosurgery. These include issues related to the usability, cognitive workload of neurosurgeons, accuracy of image registrations, the potential for intraoperative brain shift that can render preoperative images less reliable and the high costs associated with advanced imaging technologies. Furthermore, the thesis considers the learning curve and the need for specialized training to efficiently utilize these sophisticated systems, alongside evaluating the impact of these factors on patient access to cutting - edge surgical care.

Through a comprehensive review of current literature and surveys, this thesis endeavors to provide a balanced perspective on the scope and limitations of image guided neurosurgery. By acknowledging both its groundbreaking achievements and the hurdles it faces, the thesis aims to outline a roadmap for future research and development efforts in this field. Ultimately, this work aspires to contribute to the ongoing discourse on optimizing the integration of advanced imaging technologies in neurosurgery, with the ultimate goal of enhancing patient care and surgical outcomes in the complex and evolving landscape of neurological surgery.

CHAPTER 2

LITERATURE REVIEW

2.1 Historical development of IGNS

According to the Oxford Universal Dictionary, the term navigate means "to drive a ship". The earliest navigation used visual landmarks as a guide, then came the invention of the compass by the Chinese with further development to coastal maps and charts for sea navigation. Further technological advances were required such as instruments to measure the altitude of the stars and planets. In the 18th century, instruments to measure celestial angles like the sextant and angular measurements became more accurate. Thus, technological advances determined the progress of navigation both on land, sea as well as the brain.

The pivotal technological advancements that made brain navigation useful and safe started from the precise method of preparing thin slices of the brain to obtain accurate anatomical information of neuroanatomy of the deep brain structures. Second came establishment of the cartesian coordinate system of localization which allowed the precise measurement of brain structures and this allowed the construction of three-dimensional maps and atlases. From this information, in the seventeenth century, philosopher/mathematician Rene Descartes developed a coordinate system (6) for determining a point in 3 dimensional space and only after several hundred years, this method was applied to brain exploration. The earliest sketch of a skull with three coordinate axes that could correspond to the same axes of the brain was drawn by Leonardo Da Vinci in the late 15th century (7) The earliest instruments for brain localization were designed to reference the surface of the skull and its relationship with the brain. The major sulci of the brain were localized to place an opening in the skull over the exact same point but the deeper structures could not be explored accurately until a precise coordinate reference system was established and a stereotactic instrument was designed.

The history of image guidance consists of individuals confident not only in their surgical capabilities but in their ability to apply technological advances to reliably assist in navigation through the brain. Horsley and Clarke made the first stereotaxic apparatus for operations on animals (Figure 1), but long before they published their reports, on March 1889, Zernov, the professor of Anatomy at Moscow university created an encephalometer, the Zernov frame, (Figure 2) intended for anatomical studies and neurosurgical precision on the human brain. It employed a system of polar coordinates to determine the position of deep, as well as superficial structures. Its first human use was in 1889 when it was used to drain an intracranial abscess.(7)

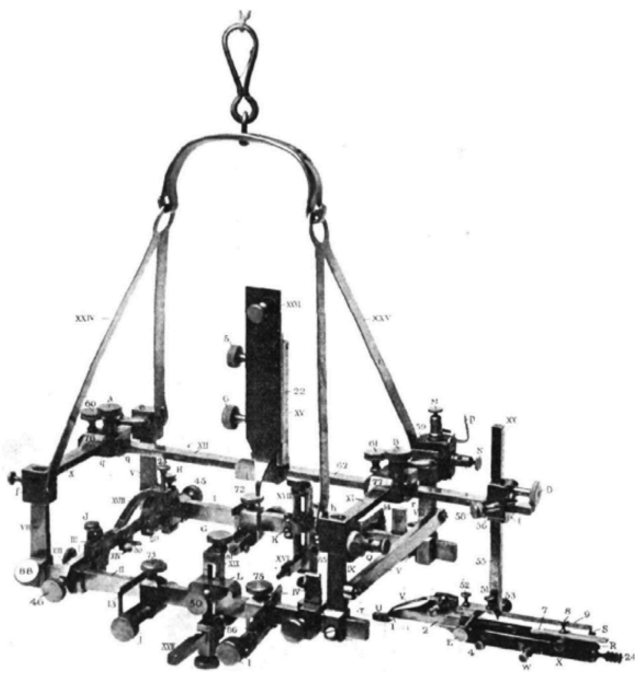


Figure 1: The Horsley and Clarke frame used stereotactic calculations based on Cartesian coordinates to localize intracranial targets in animal experiments.Thomas and Sinclair, "Image-Guided Neurosurgery."

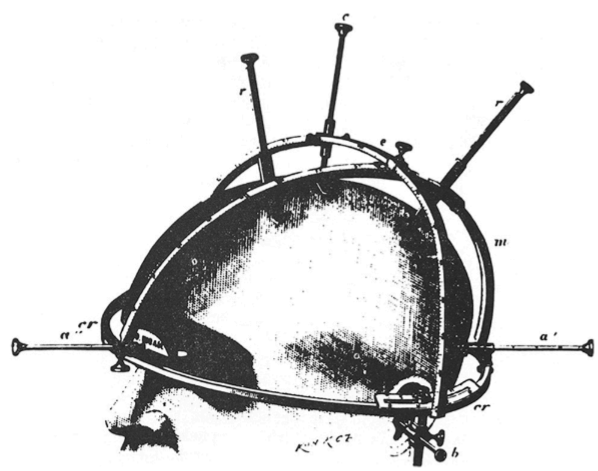


Figure 2. The Zernov frame, created in 1889, used superficial anatomic landmarks to predict the location of intracranial targets. Thomas and Sinclair, "Image-Guided Neurosurgery."

Reported in 1891 by Altuchov (Zernov's follower), the encephalometer was used successfully on a patient with severe head injury and Jacksonian seizure at the Yauzskaya hospital. A burr hole was made to expose the left Rolandic fissure and its localization was determined with the help of the encephalometer. More adjustments were made later on to treat patients with lesions and also to determine the cerebral gyrus. Postmodern findings confirmed the precision of the stereotaxic apparatus. (8) . Then in 1906, Robert Henry Clarke applied mathematical principles to neurophysiology for the invention and construction of an apparatus which allowed Sir Victor Horsley (a British surgeon) to make electrolytic lesions in the roof nuclei of the cerebellum. An

atlas was designed by Clarke and Horsley based on photographs of sections to be used in conjunction with the instrument in order to make lesions on desired points of the brain of a cat / monkey. However, although more accurate than Zernov's encephalometer, this device was never used in surgery and was instead limited to experiments involving cats and monkeys (9)
Although Clarke perceived the method's potential use in human surgery in 1920, it was not until a quarter of a century later that Dr. E.A. Spiegel, neurosurgeon at the Temple School of Medicine in Philadelphia, USA, actually employed it in surgery on humans. Spiegel became interested in developing stereotaxic apparatus for humans due to the poor state of early psychosurgical operations like the Frontal Lobotomy which used a probe to sweep the frontal lobes side to side , interrupting the white matter causing serious complications such as hemorrhage and epileptic seizures.
In 1946, Dr E.A. Spiegel and Dr. H.T. Wycis, performed stereotactic surgery in humans (Figure 3)using an imaging technique that permitted direct visualization of anatomic landmarks in individual patients (10) Ventriculography, previously invented in 1918, provided a method to visualize deep structures by taking an x-ray of air or contrast medium introduced into the ventricles (11). This was useful for the identification of structures in the thalamus and basal ganglia because of their stable relationship to the topography with intracranial reference points from ventriculography, such as the pineal gland, to perform a thalamotomy. There was a need for greater surgical precision to reach the deeper brain structures and this was the motivation for Speigel to begin work on the first stereotaxic instrument designed for use in humans. (12)

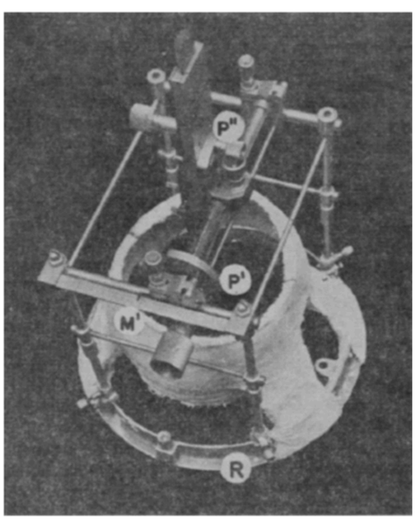


Figure 3. The Spiegel and Wycis frame was used to perform the first stereotactic operations in humans

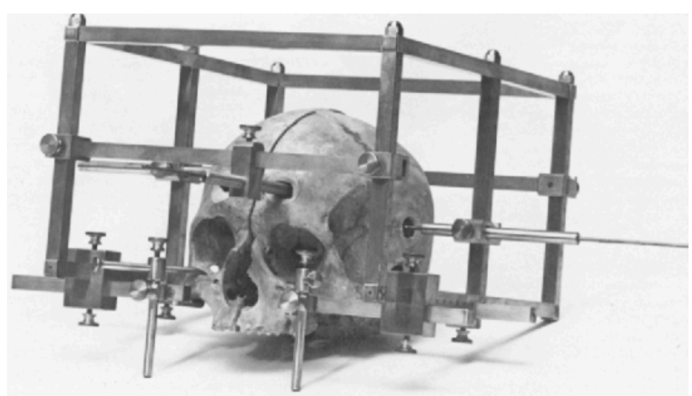


Figure 4: The first human stereotactic apparatus, designed by Mussen and built about 1918. Picard, C., Olivier, A. and Bertrand, G., 1983. The first human stereotaxic apparatus: the contribution of Aubrey Mussen to the field of stereotaxis. Journal of neurosurgery.

The first human stereotaxic apparatus was designed by Aubrey T. Mussen around 1918 (Figure 4). Mussen wrote to his son, an engineer, who was enquiring about his father's apparatus: "It must be the first instrument made for the human brain because at that time no one was interested in it. My idea at that time was to make a complete instrument of the human brain and then make an atlas of the human brain like in the cat. Then you could locate any structure in the human brain by looking at the atlas and it was my thought that if there was a tumor in the brain that could not be located, you could send an electrode in and get the reaction of normal brain and the difference if you came to the tumor. And then by making a number of degenerations with the galvanic current you might be able to destroy the tumor. And all this could be done through a 5 mm trephine in the skull and puncturing the dura without exposing the brain at all. "(13)

In 1952, Prof. Spiegel and his pupil Dr. Wycis, following their application of the Horsley-Clarke apparatus to the human stereotactic neurosurgery, realized that this surgical pattern required more precise planning based on brain landmarks instead of cranial landmarks used (12) . Furthermore, to facilitate the identification of specific landmarks, researchers utilized fixed brain specimens post-mortem, before the skull was opened. In their quest to find reliable landmarks that could be clearly identified on radiographic images for establishing reference points for the planes of section and surgical approaches in a stereotactic atlas, they employed a stereotactic frame. This frame allowed the insertion of metal rods through the skull and brain, positioned at precise distances from each other and at predetermined stereotactic coordinates across one or more planes. The calcification of the pineal gland, which could be seen on standard x-ray images, served as the initial point of reference, marking the boundaries of the intracranial space. However later discontinued its use due to its high variability, with differences of more than 12mm in the front to back axis and up to 16 mm in the axis between the ears, rendering it unsuitable for such precise operations. This pivotal moment would significantly impact the development of stereotactic neurosurgery. Thanks to the use of lumbar pneumography, it became possible to visualize crucial structures such as the posterior commissure (PC), the foramen of Monro (FM), and in certain cases, the anterior commissure (AC). By the year 1962, the year of publication of Stereoencephalotomy (Part II) by E.A Spiegel and H.T Wycis, the standard stereotactic reference system was already based on the anterior commissure line and the posterior commissure line (AC-PC) or the intercommissural line (IC) due to the work of Jean Talairach, a visionary French psychiatrist and neurosurgeon (14). The use of stereotactic frames was later significantly expanded by Dr. Lars Leksell, professor of Neurosurgery at the Karolinska Institute in Stockholm, Sweden, who also modified the Horsley and Clarke device for use in functional neurosurgery. This system differed slightly from that of Spiegel and Wycis as it used polar coordinates instead of a Cartesian tricoordinate system (15) The clinical use of stereotactic frames in functional neurosurgery continued to expand in the 1950s and 1960s with the development of procedures to treat movement disorders, pain, epilepsy and psychiatric disorders. The adaptations and technical improvements of the initial systems continued with the contributions of Spiegel and Wycis followed by those of Leskell, Riechert and Mundinger, Hassler and associates, Talairach and coworkers, Schaltenbrand and Bailey , Kandel, Niemeyer and Velasco-Suarez. This work established what may be called the first great era of stereotactic surgery.

2.2 Evolution of Imaging modalities in neurosurgery

In 1875, physicist and mechanical engineer Wilhelm Conrad Rontgen made it possible to look through the skull and other parts of the body in a noninvasive manner when he discovered a frequency of electromagnetic radiation to which soft tissues of the body were transparent. He named this discovery the “X-ray”, one of the most antique diagnosis tools for cranial and brain pathologies (16) . Shortly following Röntgen's groundbreaking discovery, Fredor Krause became the pioneer neurosurgeon to incorporate X-ray imaging into his medical practice. Utilizing this method, Krause examined tumors located at the skull's base and executed procedures like ventricular drainages. In 1907, he introduced his innovative X-ray techniques to the world through the first neurosurgery textbook, “Chirurgie des Gehirns und Rückenmarks.”(17) This was followed by the procedure named ventriculography by Dr. Walter E. Dandy for ventricular system visualization. Today, the quality and capability to produce radiographs have significantly advanced to contemporary fluoroscopy systems, capable of taking as many as 30 images per second. This enhancement enables the execution of surgical procedures in real time, including digital subtraction angiography, which has been accessible globally since 1980.

The use of radiographic visualization and the translation of the stereotactic coordinates from a brain atlas were plagued with errors that were difficult to overcome. The potential utility of frame-based stereotactic neurosurgery increased dramatically with the advent of CT in the early 1970s by Godfrey Newbold Hounsfield. James Ambrose, a radiologist at Atkinson Morley Hospital in London, collaborated with Hounsfield on scanning animal tissues and preserved human organs. This partnership resulted in the debut of the first CT scanner at his hospital in 1971, producing the initial human clinical outcomes with a CT scanner. It's reported that Hounsfield was both amazed and bewildered after scanning a patient's head at the Wesley Pavilion of Northwestern Memorial Hospital in Chicago, when he encountered an image of a hypertensive hematoma with a level of clarity never seen before (18).

With the introduction of CT imaging ,detailed three-dimensional (3D) imagery of the intracranial space and associated pathology was now available for the first time. Three- dimensional imaging provided surgeons with the ability to directly visualize brain anatomy and intracranial pathology. With CT, one became able to define true three- dimensional structures from planar computerized images. Stereotaxy had evolved from the definition of specific points in three-dimensional space into a realm of data acquisition enabling complete three dimensional surface and solid volumetric definition. The use of iodinated contrast material made it possible the separation of regions of tumor or other abnormalities resulting in blood brain- barrier breakdown as opposed to more normal definition of neural structures in the brain. Significant improvements in CT scan techniques through both hardware and software components enabled a steady progression of image quality and image resolution through the 1970s and 1980s.

In 1968, the inception of the first Augmented Reality (AR) device, dubbed The Sword of Damocles, was the brainchild of Ivan Sutherland and Robert Sprouli. This pioneering technology paved the way for image-guided neurosurgery. However, it wasn't until 1985 that AR found its initial application in neurosurgery, through an advanced microscope that combined 2D preoperative CT slices in a monoscopic view within the lens of a conventional operating microscope (19)

The advent of CT imaging resulted in an increase in the number of procedures neurosurgeons were able to perform, leading to the development of a stereotactic head frame that was able to localize any point on the CT scan through the use of a localization system fixed to the patient during image acquisition and surgery. Although changes in some frames from the pre-CT era such as the Leksell frame have enabled the utilization of CT data, other frame systems were created to specifically utilize CT data for biopsies and, eventually, for guidance of craniotomies.

This stereotactic head frame was subsequently incorporated into the Brown-Roberts- Wells stereotactic instrument (20) which was then later modified into the Cosman- Roberts-Wells (CRW) arc system with a more open architecture to facilitate multiple approaches to a wide variety of points scattered through the region of interest during craniotomies.

In the 1980s, MRI developed from the understanding of nuclear magnetic resonance, which provided surgeons with higher resolution images of intracranial targets. Leksell was one of the first to develop a frame composed of non ferromagnetic materials that was suitable for use in MRI. MR imaging required significant modification of the materials used for frame construction due to their utilization with strong magnetic fields. The materials used for fiducial object definition were quite different from those that could be used within the CT environment. The Leksell frame was made to be compatible with multiple different surgical instruments, and the use of stereotactic procedures was expanded to include MRI-guided biopsies and endoscopy (21) .Although these systems enhanced the surgical localization of intracranial targets, the frame itself created a major drawback because it had to be fixed to the head during the surgical procedure, thus mechanically obstructing the surgical field and potentially limiting surgical dexterity.

The initial frameless neuronavigation system was developed by Dr. Eihu Watanabe (Figure 5), a neurosurgeon at the University of Tokyo, Japan, in 1987. This system featured a six-joined sensing arm attached to a stable base, linked to a computer that calculated the arm’s position in relation to pre-obtained CT images. Each joint incorporated a potentiometer that generated an analog electrical signal proportional to the joint’s angle. These signals were converted into digital form, processed by the computer, which then calculated the 3D position of the sensing arm using the angles and lengths of its segments (22). The system was employed to map out the 3D coordinates of the patient's head prior to initiating surgery, enabling surgeons to acquire real-time positional data that was directly overlaid on the preoperative CT and MRI images, visible on an intraoperative computer screen.

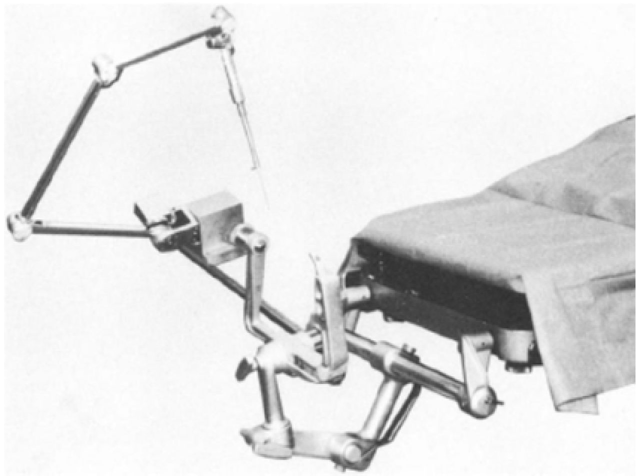


Figure 5. The sensor arm from the Watanabe neuronavigation system attached to a Mayfield skull clamp. Thomas and Sinclair, "Image-Guided Neurosurgery."

Further incorporation of imaging modalities into the CT and MR imaging frame-based environment has continued over the last decade. The utilization of positron emission tomography and single-photon emission CT as well as modifications of MR imaging such as functional MR imaging, MR spectroscopy, and dynamic gadolinium infusion MR imaging also enhance the quality of imaging information for the guidance of these procedures. The incorporation of other functional imaging modalities such as single photon emission CT scans performed with motor or speech task, the contribution of transcranial magnetic stimulation for precise motor or speed ,mapping preoperatively, the higher resolution spatial definition acquired with vector-evoked responses and electroencephalography all provide variable enhancement of our neuro anatomical functional imaging of the brain to improve the safety and efficacy of neurosurgical procedures.

This entire revolution in stereotactic neurosurgery culminates in the current intraoperative imaging systems such as the intraoperative MR, which enables real-time updating of soft tissue shifts and of current anatomical information into the operating room environment to guide ongoing neurosurgical procedures.

2.3 Image - Guided Neurosurgery

Over the past ten years, the adoption of image-guided navigation systems in surgery has grown significantly. These systems, which utilize previously captured medical images, offer numerous advantages, including enhanced precision, shorter procedure times, improved patient quality of life, lowered morbidity rates, and reduced costs for both intensive care and hospital stays. Nowadays, image-guided systems play a crucial role in assisting surgeons with both the planning and execution of surgeries, offering precise insights into the patient's anatomy and functionality throughout the procedure. Specifically, in neurosurgery, these procedures depend on elaborate preoperative planning and a complex intraoperative setup. This encompasses a variety of multimodal assessments, including anatomical, vascular, and functional explorations, alongside a growing array of computer-assisted systems being integrated into the surgical workflow.

The follow up of a patient who undergoes a neurosurgical procedure is an illustrative example of the complexity of the medical decision process and this complexity is related in particular to the heterogeneity of the data produced at different stages of the clinical follow-up.

Several investigators have pursued novel technologies of interactive image-guided neurosurgery in order to provide accurate intraoperative cranial navigation without being constrained by the design limitations inherent to stereotactic frame systems. These systems consist of five fundamental parts:

- A method for the registration of image space to physical space
- An interactive localization device
- A computer and interface
- Methods of real-time intraoperative feedback
- Robotics

2.3.1 Registration

For surgeons to access crucial data about the positions of surgical objectives, neuronavigation systems need to precisely convert chosen patient coordinates during surgery to the matching imaging coordinates found on preoperative CT or MRI scans. This is accomplished through a technique called registration. Registration calculates a direct mapping between the coordinates in both spaces, ensuring they align with the same anatomical site. Both frameless and newer, armless systems use this method to match real-world space to image space. After completing the registration process, two additional methods can be utilized to process or adjust the information within these image volumes, effectively changing the manner in which the data is presented. The first method, reformatting or reorientation, involves slicing the image volume cube along a different axial direction than the one initially selected for its two-dimensional slice display. The second method, rendering, offers an alternative approach to visualizing some of the information from the original image volume data cube. By defining a surface, such as the skin/air interface or the skull/skin interface, this surface can then be visually represented on a two-dimensional video screen in a way that mimics the appearance of a three-dimensional object captured in a photograph, complete with perspective.

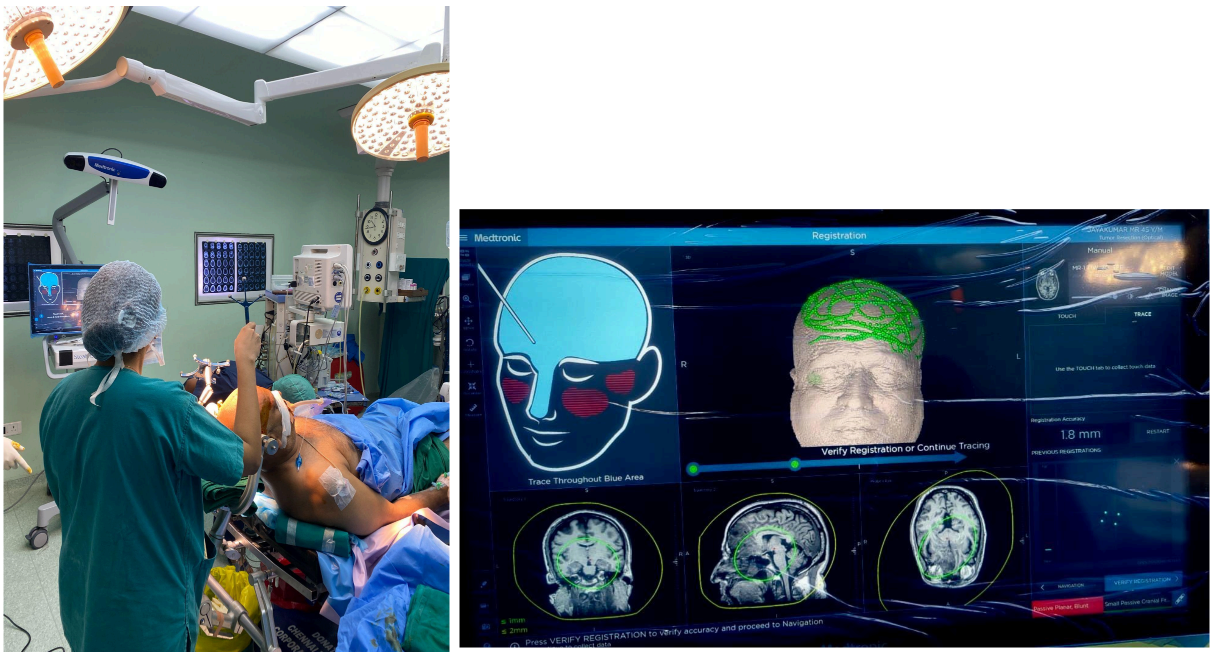


Figure 6. Image registration using optical neuronavigation, Medtronic stealthstation. Photo taken at VHS hospital, Chennai

For successful registration, it's essential to establish a shared reference frame between the space of the digitizer (also known as device space) and the image space. Within this scenario, a digitizer refers to any device capable of creating a digital model of an object by sampling a discrete selection of points from the object. A variety of registration techniques offer alternative methods for achieving the mapping of images to each other and to physical space. As seen on Table 1 , they may be classified into several types.

Table 1 : Registration techniques

Point-based

- Intrinsic
- Extrinsic
- Nonrigid
  - Fiducials
- Rigid
  - Fiducials
  - Stereotactic frames
- Curve and surface
- Moment and principal axes
- Correlation
- Interactive
- Atlas

Point based registration methods define corresponding points in different images and physical space, determine their spatial coordinates and calculate a geometric transformation between the volumes. These points may be intrinsic and based on patient-specific anatomical landmarks (23). While enabling registration to be entirely retrospective, identifying and defining anatomical landmarks has turned out to be a time-consuming task prone to considerable inaccuracies. On the other hand, registration methods that rely on external point-based systems, using markers acquired artificially like stereotactic frames or fiducial markers, do not permit the retrospective registration of images. These markers can be engineered for optimal or semi-automatic recognition, facilitating the easy extraction of their locations from medical images. Two types of fiducial markers have been used for extrinsic point-based registration: mobile markers that are taped or affixed to soft tissue such as scalp and skin and rigidly affixed markers that anchor to the skull or other bone. Mobile markers are easily affixed to soft tissues but are associated with inconsistent registration accuracy. Rigidly affixed markers require minor surgical intervention for their application but this disadvantage is offset by the dramatically increased level of registration accuracy afforded by rigid fixation (24). During surgery, these fiducial markers act as reference points in the digitizer space, which are aligned with their equivalent positions in the image space. To associate these points with one another, a transformation matrix is utilized. This matrix is applied to a specified point in the digitizer space to mathematically align it with the matching coordinates in the image space. A minimum of three fiducial markers is required to formulate a transformation matrix, although it is common practice to use more than three to enhance precision. Utilizing a larger number of fiducials enables the system to identify the most accurate set of three markers, based on the smallest root mean square error across the two sets of coordinates. These systems have fallen out of favor due to the invasiveness of embedding fiducials in bones and advancements in accuracy through surface contour matching and skin-affixed fiducials. Modern alternatives include temporary adhesive masks adorned with multiple fiducials for use during registration. Applied after securing the head to the surgery table, these masks can be easily removed post-registration, avoiding interference with the surgical area. (25)

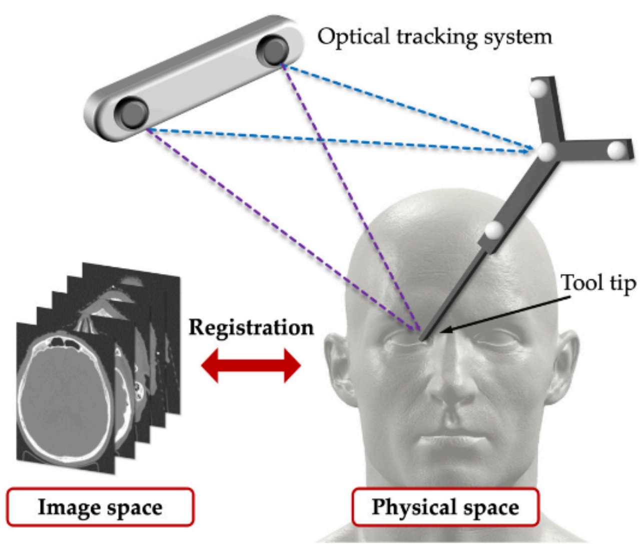


Figure 7. Overview of the calibration and registration. Lin, Lei, and Yang, "Modern Image-Guided Surgery."

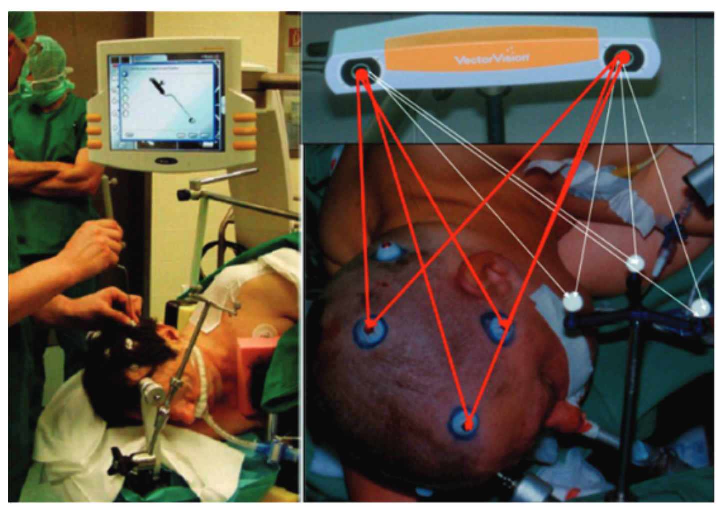
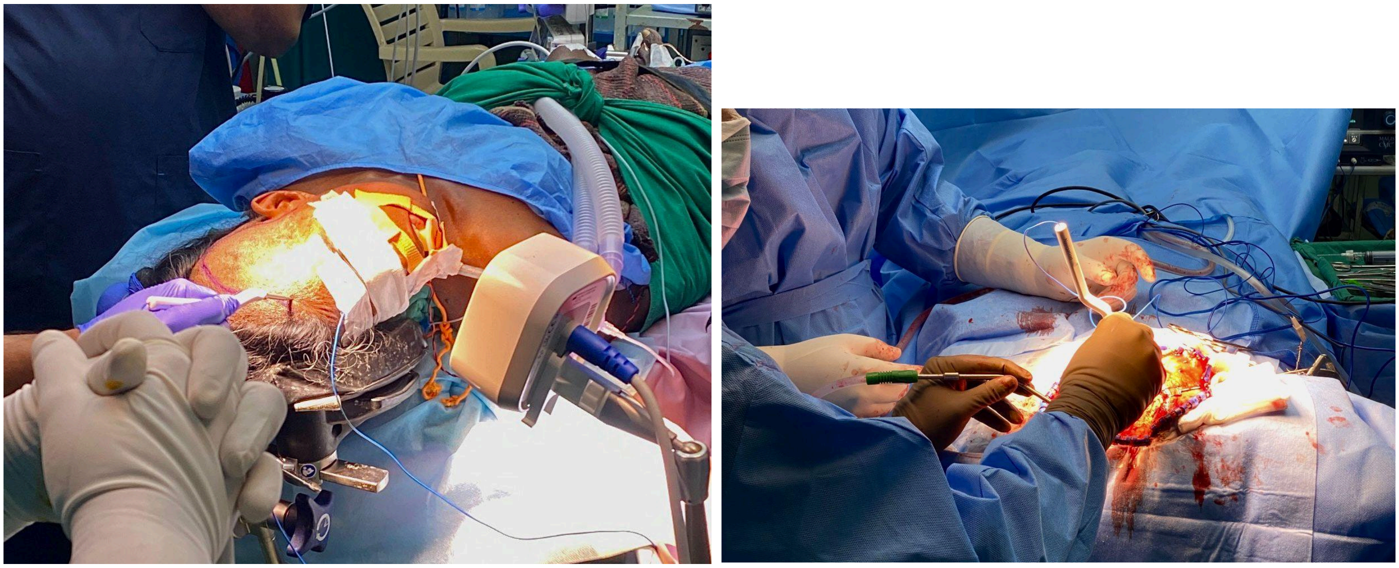


Figure 8. Typical preoperative registration using skin markers (fiducials) and an optical camera system. Schulz, Waldeck, and Mauer, "Intraoperative Image Guidance in Neurosurgery."

Surface contour matching involves aligning corresponding surfaces in physical and image spaces by minimizing the distance of specific features between them. This process calculates a geometric transformation to align the patient's surface with a 3D model derived from imaging data. Collecting surface data entails marking enough points on the patient using a pointer or a laser contouring tool. A laser pointer sweeps across areas like the forehead, skull, and eyes, while a camera system captures the laser's reflection. These points are then integrated into a computer-generated surface model based on CT or MRI images. Advances in technology, including scanning more points on the skull, have enhanced the precision of surface contour matching. Due to its increased accuracy and user-friendliness compared to the fiducial implantation, surface contour matching, frequently paired with skin-affixed fiducials, has become the preferred registration method

2.3.2 Interactive Localization Devices

To align image space with physical space, the use of a physical pointer to pinpoint the points or surfaces for registration is essential. These interactive localization devices (ILDs) represent the second crucial component of any intraoperative cranial navigation system. Prior to surgery, images from CT scans, MRIs, and CT or MR angiograms are uploaded to a computer planning system for examination by the surgeon. These images are integrated using advanced software designed for the neuronavigation system to create a 3D representation of both the cortical and subcortical structures. This 3D model aids in assessing surgical risks, choosing the most appropriate treatment approach, and determining the ideal path for the surgical intervention . After completing the preoperative planning, the reconstructed 3D image is projected on a monitor in the surgery room, helping to pinpoint the exact surgical site in relation to important brain structures. With the patient positioned for surgery, the system's digitizer is capable of tracking the surgical instrument's location, effectively turning it into a navigational tool during the procedure. The digitizer computes the tool's spatial location and relays this data to the computer, enabling surgeons to observe the instrument's position against the 3D model on the screen in real-time (26). Interactive localization devices are divided into linked or nonlinked depending on whether or not they require an unbroken physical connection between the device and the patient.



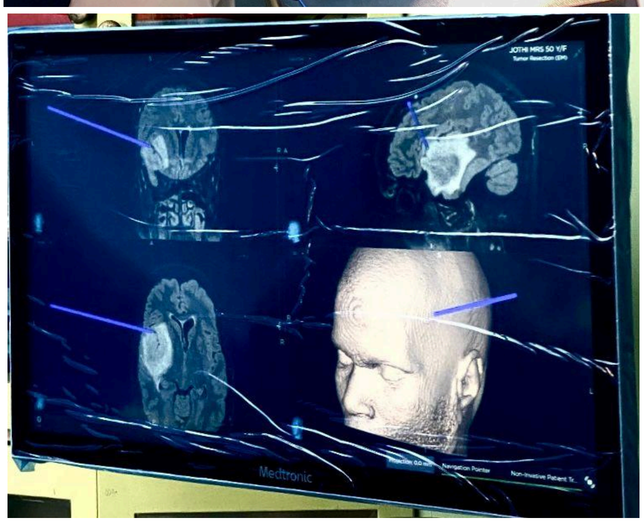


Figure 9. Electromagnetic Neuronavigation, Medtronic stealthstation used in VHS hospital, Chennai. Small electromagnetic sensors are attached to surgical instruments (top right). These sensors generate a magnetic field detected by a reference field generator placed near the surgical site (top left). The position and movement of the instruments are tracked in real-time and displayed on a monitor, overlaying the instrument's location on the preoperative images.

Linked systems began with stereotactic frame-mounted aiming arc assemblies, have included active robotic and passive articulated localizing arms and currently include intraoperative tomography with CT and MR imaging (27). Nonlinked ILDs began with techniques of sonic triangulation on spark-gap emitters and have substituted infrared light for sound in the infrared light-emitting diode devices triangulated on by linear charge-coupled device three-camera arrays (28). TThe initial system utilized sonic digitizers to align patient coordinates with those in image databases. It determined the location of a probe attached to the surgical tools by calculating the time it took for an ultrasonic pulse, emitted from a spark gap on the navigation probe, to reach at least three recording microphones. A spark gap, which is made up of two conductive electrodes with a small air gap between them, generates a sound when a spark travels across the gap. The position of the spark gap was then deduced by comparing the arrival times of the sound wave at each microphone. A significant drawback of this system without mechanical arms was its reliance on a constant speed of sound for precise accuracy. Variations in temperature, humidity, surrounding noise, and echoes within the surgical setting posed significant challenges and were key limitations in the advancement and integration of this armless navigation technology (29).

A technique of surgical guidance employing “machine vision”, was proposed by Heilbrun (30), wherein the three-dimensional position of an object in space is determined from its differential position on two-dimensional video images viewed from two different angles. Two video cameras located approximately 1 m apart are aimed at the surgical workspace and a video localizer consisting of a set of eight fiducial objects in a box like configuration of known dimensions is placed within the field of vision. A photogrammetric projection algorithm defines the three dimensional coordinates of the eight fiducial objects. Subsequently, the position and field of view of the video cameras remain unchanged and the three-dimensional position of any object in the surgical work space of their field can be determined and tracked. The advantages of this method are its flexibility, its potential to track standard surgical instruments as stereotactic pointers with minimal modification and its reliance on readily available video technology. They also do not require a direct line of sight from emitter to sensor, unlike sonic and optical systems, however, there still are problems with accuracy due to the need to maintain a homogenous magnetic field. Any sources of electromagnetic radiation or ferromagnetic substances that are frequently used in surgical instruments can distort the magnetic field and impair accuracy (31).

Numerous research groups have explored the application of Light-Emitting Diode (LED) Optical Triangulation as a novel method for optical positioning. By attaching two or more Infrared Emitting Diodes (IREDs) to a surgical tool, it becomes possible to monitor the tool's spatial location over time using a triangulation method. This method involves the use of three or more specialized linear charge-coupled devices, each containing 1000 to 4000 elements and equipped with cylindrical lenses. Optical triangulation methods offer high levels of accuracy and precision, demonstrate remarkable resilience in the chaotic environment of a surgery room, and are versatile in application. Unlike sonic digitizers, the performance of IRED arrays is not affected by variations in temperature or humidity. Furthermore, interference from surgical lighting has not been an issue, and the infrared wavelength of the emissions does not interfere with surgical procedures (32).

During a procedure, the 3D reconstruction created by the neuronavigation system can also be superimposed onto a head up display in the optics of the surgical microscope.. The 3D model is aligned with the actual surgical field through registration techniques that first align the soft tissue contours of the patient’s head to the corresponding CT or MRI soft tissue anatomy. Once the surface of the brain is visible, it is possible to re-register the image to improve accuracy by aligning the visualized cortical vessels with the corresponding vessels in the 3D model obtained using CT or MR angiography. To identify lesions located deeper in the brain, the tip of a surgical probe fitted with LEDs is able to provide depth information to help orient a surgeon throughout the procedure (33). The tip of the probe is placed on an area of interest within the open surgical cavity and its current location is displayed in realtime on the 3D model displayed on the computer screen. In addition, the focal points of a surgical microscope can be used as a virtual pointer. The information from these instruments provides surgeons with a more accurate approximation of the location and contours of subcortical tumors.

2.3.3. Computer and Interface

The swift advancement of computer hardware and software serves as a key catalyst for the progress of surgical navigation systems. Given that neurosurgery represents a specialized market for many producers, significant technological improvements have emerged either through the deliberate development of systems by cooperative teams of surgeons, scientists, and engineers at academic institutions, which are then commercialized through the creation of medical supply companies, or through the ad hoc modification of technologies originally designed for different applications. The computer hardware employed tends to either be an image processing workstation that is fairly generic, commercially available, interchangeable and therefore upgradable or customized, high-performance, specialized hybrid hardware with machine specific software and peripherals. The current leading approach for planning treatments and displaying information during operations involves using multiplanar slice images that refresh quickly, along with rendered images that are easy to understand and simple to compute. There's still a lot of experimentation with "heads-up" displays, but finding a solution that strikes the right balance between losing information and causing confusion from too much visual data has been challenging. The way modern digital imaging scanners connect with these display systems often leads to inconsistency and failure. The design of treatment planning software and image reformatting options in terms of surgical usability is an area receiving significant attention and improvement. Crucial to making advancements in this area is the direct involvement of a neurosurgeon to guide the clinical aspects of these technologies. Image display and manipulation for surgical applications differ greatly from those of radiology. Surgical applications have much greater time constraints and a greater dependence on robust automatic algorithms. However, intraoperative applications do not need the flexibility of image gray-scale manipulation required for radiologic displays, since by the time of surgery all diagnostic information from the images should already have been extracted. When operating, the surgeon wants to be able to look from the surgical field to the monitor and see the present surgical site, locations of sensitive structures relative to the present surgical position and some information about the present surgical trajectory with the information being as accurate and current as possible (34).

2.3.4 Real Time Intraoperative Feedback

After establishing dependable techniques for determining the precise location of objects in space, these methods can be enhanced by adding real-time feedback from the area being operated on. While preoperative digital imaging data provides a snapshot in time when matched to the actual physical space, it fundamentally represents past information. This data can quickly become outdated in the operating room as the surgeon's manipulation of tissues alters the physical environment being addressed.

By integrating real-time feedback from the surgical work space, the feedback loop of intraoperative cranial navigation can be completed as this new information is employed to refresh and update the registered image data being used for guidance Table 2 . A number of intraoperative visualization and data gathering techniques can be digitized in the form of digital video images which may be registered to the preoperative images. These databases are derived from the output of intraoperative estimation mapping and electrocorticography, endoscopy and microscopy, ultrasonography and tomography with CT or MR imaging. To this end, image-to-image registration between pre- and intraoperative images is critical to enable the useful translation of planning data. A relationship between these images and the physical space of the patient (image-to-patient registration) is also necessary to ensure that the surgeon is making physical movements that are in agreement with the planned surgical approach. Navigation systems are based on image-to-patient registration and can track the location of the surgeon's tools and display them on pre- or intraoperatively acquired images, creating a direct and useful application of imaging during the procedure (35)

Table 2: Integration of Real-Time Data

Electrophysiology	
	Intraoperative stimulation mapping
	Electrocorticography
	Microelectrode recording
Microscopy and endoscopy	
Ultrasonography	
Tomography	
	CT
	MR imaging

Image-guided surgery historically used stereotactic frames to stabilize the head for brain surgery. The frame allows a fixed and calibrated reference for tumors at depth and in relationship to diagnostic imaging and progress of treatment (36). The frame provides a stable and precise point of reference for tumors located deep within the body, in terms of both diagnostic imaging and monitoring treatment progression. Stereotactic procedures utilize a specialized ridged frame to secure the head during surgery. Traditional ridged stereotactic techniques have evolved into frameless stereotaxy, commonly known as neuronavigation. Surgical navigation can either be conducted with frame-based stereotaxy or through frameless neuronavigation systems, which employ CT or MRI scans acquired several days prior to or immediately before the surgery. During surgery, MRI has become the modality of choice for guidance of surgical instruments, aspiration devices, biopsy needles, endoscopes, curettes and electrodes and can provide images to aid in compensating for brain shift. This is due to MRI's superior soft tissue contrast and multiplanar imaging capability (37,38). Three-dimensional ultrasonography is an option for guidance during surgery because it is easy to use, requires little preparation and offers real-time images without radiation. The use of ultrasonography to dynamically re register shifting brain parenchyma during resections has been advocated repeatedly. Because of surgery, the brain anatomy may shift and deform due to lesion resection, bleeding, or fluids being drained. The extent of change is dependent on the severity of the surgery: minimal with biopsies but significant with full craniotomies. Navbavi and Handels (39) suggest the only way to compensate for this deformation and shifting is to use intraoperative imaging using modalities such as MRI, CT, US and angiography. Although MRI is the most expensive and cumbersome modality, it offers the best structural and functional information, although intraoperative three-dimensional US offers a flexible and lower cost intraoperative option compared with MRI and the US system can be fused with or compared side-by-side with preoperative CT and MRI images (40).

2.3.5 Robotics

Robotics in image-guided neurosurgery represents a revolutionary convergence of advanced technology and medical science, aimed at enhancing precision, safety, and outcomes in neurological interventions. This field leverages the integration of robotic systems with real-time imaging techniques to navigate the complex anatomy of the brain, offering surgeons unparalleled accuracy during operations.

The advent of robotics in this arena introduces a shift from traditional hands-on surgical approaches to one where surgeons direct robotic instruments that can maneuver with sub-millimeter accuracy. These systems are designed to assist in the precise removal of tumors, the correction of vascular anomalies, and the implantation of devices, among other tasks, with minimal harm to surrounding healthy tissues. Central to the success of robotic-assisted image-guided neurosurgery is the use of advanced imaging modalities, such as MRI and CT scans, which provide a detailed map of the brain's anatomy. This information is integrated into the robotic system in real-time, allowing for adjustments to be made during the procedure to account for the brain's shift or changes in the target area.

The concept consists of an image-guided robotic platform capable of both microsurgery and stereotaxy, which conducts telesurgery with the patient within the bore of an MRI scanner. Based on a master-slave paradigm, the system may include a pair of robotic manipulators operating in the magnet bore, whereas a surgeon commands the robot from a sensory immersive workstation that recreates the sight, sound and touch of surgery (41). After intraoperative imaging modalities made its way into the operating room, the idea of iMRI was developed with the goal of maximal resection of lesion through identification of residual tumor intraoperatively allowing additional surgery to be performed if necessary in the same sitting, thus preventing redo surgery weeks or months later. Furthermore, iMRI can also demonstrate intraoperative brain shift by providing an updated MRI for neuronavigation when surgery has rendered registration based on preoperative imaging data that are no longer accurate (37).

The programmable precision and strength of a machine technology enable surgeries to unfold independent of factors such as fatigue and time limitations. The idea of incorporating such a machine into neurosurgery, while interesting, is not only a formidable proposition, but also something that is accompanied by considerable risk to an already complex operating room environment. However, the notion of having such an option where performing complex tasks with a machine-based accuracy and semiautomated certainty appealed to the surgeons, particularly if such a system could be used to aid in the performance of surgery. The fundamental questions that need to be addressed in advance are those associated with patient safety, surgical sterility, regulatory approvals, ethical standards, financial cost, dedicated engineering proficiency, seamless integration of the tools into surgeon’s training, and execution of surgical procedures at par or better than in a conventional neurosurgery (42).

The goal of postoperative imaging is to assess results of the intervention. Diagnostic imaging techniques used in the planning phase can help to determine the success of the intervention such as the extent of tumor resection, to determine occurrence of complications, and to plan follow-up treatment (35). The capability to assess the remaining tumor mass following surgical removal is crucial, as it significantly predicts the likelihood of tumor return, particularly with gliomas. The detailed soft tissue imaging provided by MRI, along with the insights into the impact of surgery on critical brain regions revealed by functional MRI (fMRI), are instrumental in evaluating the outcomes after surgery (43).

2.4 Imaging modalities in Image-guided neurosurgery

For more than a decade, neurosurgeons have become increasingly dependent on image guidance to perform safe, efficient, and cost effective surgery. Neuronavigation is frame-based or frameless and requires obtaining computed tomography or magnetic resonance imaging (MRI) scans several days or immediately before surgery. The integration of these imaging techniques into neurosurgical procedures has revolutionized the way surgeries are planned and executed, significantly improving outcomes for patients. Computed CT and MRI were combined with framed based localization techniques to permit quantitative navigation within the three dimensional volume defined by the images. Contemporary state-of-the-art surgical decision making is not conceivable without comprehensive, patient-specific morphologic, functional, and metabolic information. This complex information cannot be obtained by means of any single imaging/diagnostic modality alone.

2.4.1 Intraoperative MR- Guided Neurosurgery

MRI has been used in neurosurgery for more than 20 years and over this interval, neurosurgery has experienced a number of technical innovations. And with this advancement, it is no surprise that MR imaging is now being used to guide the performance of safe and effective surgical procedures. Neurosurgery has been at the forefront among surgical specialties in advancing the use of intraoperative magnetic resonance imaging (ioMRI)-guided surgery. The significant benefit of using ioMRI lies in its ability to enable neurosurgeons to modify their surgical strategies dynamically and almost instantly. This adaptability is crucial for compensating for brain shift, a common occurrence when the skull is opened and cerebrospinal fluid (CSF) is drained. This capability gives ioMRI a distinct advantage over traditional neuronavigation systems.

Intraoperative MR Imaging, also known as magnetic resonance therapy (MRT) was developed in 1991 as a collaboration between the Departments of Neurosurgery and Radiology of the

Brigham & Women's Hospital in Boston, Massachusetts and General Electric Medical Systems (26). It is a 0.5 - T superconducting magnet system designed with a vertically open configuration that allows surgical staff to stand on either side of the patient. The patient table can be positioned through the bore of the magnet as is the case with conventional diagnostic MR imaging gantries or through a vertical gap in the magnet. The main thrust of current MRT development involves a highly sophisticated system of image reconstruction and virtual reality presentation, giving the surgeon all of the anatomical information needed to safely resect a lesion and avoiding sensory overload. Data from different imaging modalities may be combined into a functional-anatomical data set that is manipulated as surgery progresses, using high-resolution MR updating of the spatial and anatomical information acquired preoperatively.

One challenge in the electromagnetic operating room environment is the requirement to avoid ferromagnetic materials, which are strongly attracted to magnetic fields. Instead, materials like aluminum, titanium, and ceramics, which are not ferromagnetic, are utilized. The ioMRI system also offers the unique ability to display tissue temperature as an image contrast parameter providing the significant capability to monitor and control thermal procedures, including the creation of central nervous system lesions and the ablation tumors (38).

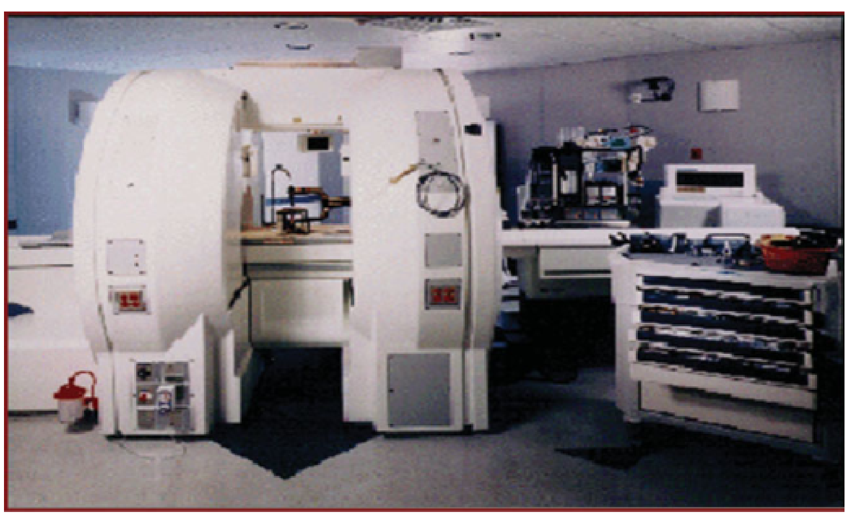


Figure 10. The 0.5T double coil design ioMRI system where imaging can be performed continuously while the surgeon operates between the coils. (Ferenc Jolesz, MD, Department of Radiology, Brigham and Women's Hospital.) [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

The quality of images produced by intraoperative magnetic resonance imaging (ioMRI) largely depends on the magnetic field strength and the gradient used. There is a trade-off between the features needed for an optimal ioMRI system and those required for producing high-quality images. High-resolution imaging is typically achieved with "closed" MR systems, while an ideal ioMRI system is designed to provide maximum access to the patient. While many ioMRI systems traditionally use lower field strength magnets (below 1.5T), there is a growing shift towards high-field (1.5T) ioMRI systems, which offer enhanced functional capabilities (44).

The principal advantage of the lower field strength ioMRI systems is related to the less strict requirements for entirely MR-compatible surgical instrumentation. In addition, the surgeon is not required to stand between the magnets in these systems. All low-field systems have reduced temporal resolution, reduced spatial resolution per unit time, and are constrained by their signal-to-noise ratio (SNR), compared to higher-field ioMRI systems. Clinically, this mandates increased imaging time to achieve image quality that is sufficient for accurate surgical decision-making (38). High image quality in diagnostic MR is related to system field strength and the homogeneity and stability of the static and gradient magnetic fields. These factors are most obtainable by decreasing the “openness” of an imaging system. In contrast, the environment best suited to surgical intervention is one with maximum access to the patient, allowing complete freedom in the interventional approach and maintaining close proximity of monitoring and therapeutic devices. These attributes are in direct opposition to those facilitating image quality. The use of MRI for intraoperative surgical guidance has required compromise between these opposing factors (45). Understanding the role of different MR system designs in surgical interventions involves recognizing two primary uses of MRI during neurosurgical procedures. Typically, MRI is employed to track the progress and outcomes of surgery. This includes evaluating whether a tumor has been completely removed during procedures like craniotomies or transsphenoidal resection of pituitary adenomas, as well as confirming the effective removal of hematomas or aspiration of cysts. These applications of intraoperative MRI usually require only slight modifications to standard imaging systems since direct access to the patient during the imaging process isn't always necessary. The primary modification needed is a surgical/MR table that can safely move the patient from the surgical position into the imaging device. However, the time it takes to position the patient in the scanner can restrict the frequency of imaging sessions when using MRI with certain systems. Often, integration with a frameless stereotactic localization system is also implemented to enhance navigation towards areas of residual tumor.

The second way MRI is utilized is to guide surgical procedures, where surgeons use the technology to direct instruments like aspiration devices, biopsy needles, endoscopes, curettes, electrodes, or laser fibers. This approach, which is more interactive, marks a substantial shift away from traditional diagnostic practices and standard imaging systems. The simplest form of this guidance might rely on retrospective data sets, using either frame-based or frameless stereotactic systems. However, there is a growing focus on employing real-time or near real-time guidance during intraoperative MRI procedures to enhance surgical precision (46).

Double Donut Configuration

A novel approach to obtaining access to a patient in a cylindrical system is exemplified in the “double donut” configuration of the General Electric Medical Systems Signa SP system, designed specifically for interventional applications. This design modifies the central part of a cylindrical system, creating openings that allow access to the patient from the sides and top at the imaging system's isocenter. Aimed at integration within a surgical setting, this product design provides sufficient space in the openings (54 cm wide) to accommodate two small- to medium-sized physicians or nurses, positioned on either side of the patient. This system offers significantly better patient access compared to traditional closed-bore cylindrical systems. Pioneering in its field, this is the first system specifically engineered for interventional guidance, and it remains the only available system that permits complete vertical and lateral access to the patient at the imaging isocenter. This innovative magnet design has been extensively utilized to both guide and monitor numerous surgical procedures (47). All instrumentation, including the operating microscope, must also be non ferromagnetic because the entire procedure is performed within the magnetic field, which adds significant cost to the surgical MR suite.

Biplanar Magnet Designs

Another method gaining popularity in the expanding "open MRI" market involves the use of a biplanar magnet design. In these systems, patients are positioned between flat magnetic poles, which allows for side access from various angles. These biplanar systems generally employ lower field permanent or resistive magnets, with field strengths varying from 0.064 to 0.3 T. However, superconducting midfield models have also been developed using this design. The access around the perimeter of the biplanar magnet is determined by the quantity and arrangement of supports that separate the two magnetic poles.

The C-arm design, developed by Siemens Medical Systems (Erlangen, Germany) and Marconi Medical Systems (Highland Heights, OH), offers extensive access around the patient's circumference. In this design, a single column on one side supports the upper pole, enabling access from the opposite side, as well as from the head and foot ends of the magnet. Some manufacturers offer biplanar systems that include two supporting posts, which slightly restrict access to the patient compared to the C-arm design. The biplanar setup provides a relatively homogeneous static magnetic field but typically operates at lower field strengths compared to cylindrical superconducting designs. The side access these systems provide is similar to C-arm fluoroscopy, facilitating procedures directed by needles or catheters. However, anterior or posterior approaches require the patient to be in a decubitus or oblique position, which may not be feasible for larger patients due to limited space between the poles of the biplane magnet. A true direct vertical approach is only achievable when the patient table is moved outside of the magnet, thus precluding the possibility of simultaneous vertical interventions and imaging (48).

Cylindrical Superconducting Systems

From the perspective of image quality, cylindrical superconducting systems offer substantial benefits in terms of magnetic field strength and homogeneity, making their widespread adoption as the standard in diagnostic imaging a deliberate choice rather than a coincidental one. Although these systems restrict patient access for performing procedures and direct visual observation, they still permit certain types of interventions. The excellent signal-to-noise ratio these systems achieve makes them particularly effective for thermal monitoring during ablation processes. Consequently, they have been utilized in various procedures, including laser and radiofrequency ablation treatments in the brain (49).

Another method of integrating cylindrical superconducting systems into interventional monitoring involves placing such a system within a surgical setting. Thanks to the rapidly diminishing static magnetic field made possible by actively shielded magnet designs, it is feasible to position a superconducting system close to a surgical workspace. This setup has been implemented by Philips Medical Systems (Eindhoven, The Netherlands) in a design where a procedure suite, equipped with nearly all the features of a traditional surgical theater, is built just outside the fringe field of a superconducting short-bore 1.5-T imaging system. Surgery can be conducted in this suite much like in a standard operating room. However, when necessary, the patient can be moved into the cylindrical imaging system for intermittent imaging. This system maintains all the advanced capabilities of a high-field system, including functional imaging and spectroscopy, while ensuring high image quality. This configuration does not allow interactive guidance of the intervention, as access to the patient is limited and direct observation by the anesthesiologist is also not possible during scanning. The use of this type of system in the future for active procedure guidance may be achieved through the application of robotic systems (50).

2.4.2 Intraoperative Computed Tomography

The CT scan is essentially an X-ray study, where a series of rays are rotated around a specified body part, and computer-generated cross-sectional images are produced. The advantage of these tomographic images compared to conventional X-rays is that they contain detailed information of a specified area in cross-section, eliminating the superimposition of images, which provides a tremendous advantage over plain films (51). The intraoperative CT imaging has a gantry mounted on rails in the floor of the operating room. For imaging, the rails in the floor allow movement in a caudocranial direction. After the patient is slid from the operating table on the transfer board, the gantry is moved towards the patient to the most caudal position needed for imaging. Thus ,it is ensured that no collision between gantry and the structure of the operation table occurs. For automated registration, the housing of the gantry is equipped with reflective markers for infrared light. Hence its position can be measured for registration purposes (52). CT is the modality of choice for interventional procedures requiring cross-sectional imaging such as needle guidance and biopsies. X-rays present difficulties for staff conducting the procedure and add to the total radiation exposure received by the patient. When combined with PET or SPECT, CT can assist in attenuation correction and provide anatomical reference points.

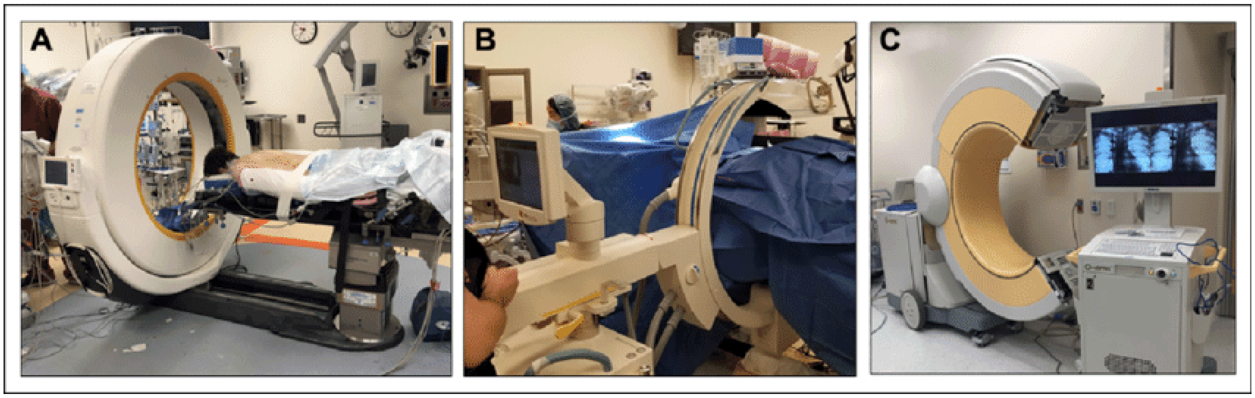


Figure 11. Intraoperative computed tomography (CT) - based 3-dimensional navigation technology systems: (A) fan beam CT, (B,C) cone beam CT. Hussain, I., Cosar, M., Kirnaz, S., Schmidt, F.A., Wipplinger, C., Wong, T. and Härtl, R., 2020. Evolving navigation, robotics, and augmented reality in minimally invasive spine surgery.

Modern scanners are capable of achieving a spatial resolution ranging from 0.3 to 1 mm, and a temporal resolution under one second. The duration of the scan varies based on the gantry's rotation speed, the pitch, and the length of the area being scanned. This capability is useful not only in surgical planning but also in providing real-time guidance during surgical procedures. Intraoperative CT scan has been available as a portable device since the early 2000s and has been used with great success in spinal surgeries. With the development of multidetector CT (MDCT), soft-tissue image resolution is improving and its use in neurosurgical suites is increasing. It can be easily incorporated into a preexisting setup and requires very little changes; some of these include lead shielding and radiolucent table top with a radiolucent Mayfield/Doro head holder (53). In spinal surgeries, iCT assists in the precise placement of screws and other instrumentation. The real-time imaging helps in avoiding critical structures such as nerves and blood vessels, thereby reducing the risks associated with misplacement. Currently, there is limited data on the uses of intraoperative CT scans. While their application in spinal surgery is well-established, their use in surgeries involving soft tissues is generally restricted to small case series that concentrate on a single pathology, primarily due to the inferior imaging quality compared to MRIs. Additionally, there is a lack of large multicenter controlled trials.

2.4.3 Magnetic Resonance Angiography

An MR imaging system is a remarkable device that can image many different attributes of tissue within the human body. In addition to proton density, relaxation time and spectroscopic and functional information, it can also be “tuned” to respond only to moving material. In MR angiography, the imaging sequence is tuned to be sensitive to motion. Hence, there are two broad classes of MR angiographic techniques that can be considered according to magnetization utilized for motion sensitization: time-of-flight (TOF) and phase contrast (PC) methods.

TOF methods primarily utilize the longitudinal magnetization component for flow encoding. It allows the visualization of blood flow in vessels without using contrast agents and utilizes the principle where moving spins entering an imaging slice show higher signal intensity because they are unsaturated, contrasting with the lower signal from stationary spins around them (54). The most common technique is based on inflow enhancement which utilizes a passive tagging scheme that results in fully relaxed blood continuously flowing into the imaging volume. Consider a region of the brain that is repeatedly being excited with a repetition time that is much shorter than the T1 relaxation times of brain tissue. Because the longitudinal magnetization does not have time to significantly recover between excitations, the signal generated by the stationary brain tissue approaches a steady-state level that is very low called partial saturation. Blood flowing into the region is fully relaxed because it has not experienced prior excitations and therefore produces a strong signal that gradually decays to a condition of partial saturation. The high contrast between the fully relaxed blood (bright) and partially saturated tissue (dark) allows easy delineation of the vasculature (55). The primary limitation of inflow-enhanced TOF-MRA is the loss of contrast as blood flows deep into the imaging volume and approaches a steady-state condition of practical saturation. . Scanning the area of interest with a sequence of 2-D images significantly reduces this issue. Yet, there are challenges in obtaining axial slices thinner than roughly 2 mm, which limits resolution. Moreover, 2-D imaging is not as effective as 3-D imaging in terms of signal-to-noise ratio (SNR). Although 3-D imaging of entire brain volumes can provide very high resolution (less than 1 mm) and strong theoretical

SNR, it is the most susceptible to partial signal loss due to saturation, particularly at points further away from where blood enters the imaging area. Various methods have been created to overcome these limitations, such as selectively diminishing brain tissue signal or boosting the blood signal. One method, called multiple overlapping thin slab acquisition (MOTSA), strikes a balance between multiple 2-D images and single-volume 3-D images by obtaining several slender 3-D volumes. Another widely accepted technique involves magnetization transfer saturation to specifically decrease tissue signal while preserving the blood signal. A third strategy employs an MR imaging contrast agent like gadolinium-DTPA to selectively increase the signal within blood vessels (56).

PC-MRA uses the phase shifts introduced to nuclei with motion in the presence of a magnetic field gradient. A bipolar magnetic field gradient will induce a phase shift to nuclei moving along the gradient dependent on the velocity, as well as acceleration and higher order motion terms. More complex gradient waveforms enable sensitivity to specific motion terms such as velocity or acceleration. By constructing an image in which the intensity is proportional to the phase shift of the nuclei, it is possible to create an angiographic image related to the flow properties of blood (or other liquids such as cerebrospinal fluid). The PC-MRA is a powerful technique and allows for encoding of flow in one or many directions in such a way that the velocity sensitivity can be chosen depending on the vessel of interest. This technique also allows for quantification of flow velocity and flow rate, which is not generally available with other angiographic techniques (57). Because PC MRA does not rely upon signal magnitude differences, it does not suffer from signal loss with volume penetration and is therefore well suited to image the venous and arterial systems simultaneously.

One significant benefit of phase-contrast magnetic resonance angiography (PC MRA) in the context of neurosurgery guided by imaging is its ability to capture both MR angiograms and standard anatomical images at the same time. Additionally, since both image types are derived from the identical dataset, there's no risk of images not aligning correctly due to patient movement between scans. PC MRA proves to be an effective and attractive method when a comprehensive image of both brain anatomy and blood vessels is needed to strategize a surgical procedure that will steer clear of major vessels. However, for a more intricate view of the arterial structure, a high-resolution, focused time-of-flight (TOF) acquisition may be more suitable. A broad advantage of using MR angiography is its noninvasive nature, allowing a patient to undergo a single imaging session that captures both anatomical and vascular details, either one after the other or at the same time. This approach not only enhances patient care but also reduces imaging costs.

2.4.4 Positron Emission Tomography (PET)

Developments in imaging techniques have dramatically improved the ability to diagnose and treat patients with neurological disorders. Techniques such as single-photon emission tomography (SPECT) and positron emission tomography (PET) have been developed to allow in vivo study of brain function and metabolism. PET is a computerized tomographic imaging technique that allows accurate and sensitive in vivo visualization of metabolic processes and measurement of the local concentration of radiotracers. This makes PET a critical imaging modality for diagnostic improvements and therapeutic studies. The integration of PET in the management of neurosurgical disorders represents a unique way to provide metabolic and functional information that can be used in neurosurgical guidance. PET is a technique in which a radiotracer is administered to a patient , accumulates in the tissues and is visualized by means of a camera (58). It differs from conventional nuclear medicine in that the radiotracer contains an isotope emitting positive particles or positrons which have a charge and a mass equivalent to those of electrons. In tissues, the emitted positrons collide with the electrons and both particles disappear by annihilation. This phenomenon is accompanied by the emission of two gamma rays of fixed energy diverging in opposite directions. These two gamma rays are registered in time coincidence by detectors in the PET camera or tomography, which allows determination of the precise location and quantification of isotopes in the tissue. After acquisition of a sufficient amount of data, a computer can generate images that can be visualized in tomographic planes and that reflect the regional distribution of the tracer.

Different approaches have been used to take advantage of the metabolic information provided by PET to guide neurosurgical interventions. They range from the simple visual projection of information from standard PET images to the use of PET in stereotactic conditions. Visual analysis of PET-FDG images was reported to be used to provide a pathological sample in brain lesions (59). This report illustrates the complementary role of PET and CT or MR imaging for selecting a target for brain biopsy. Stereotactic PET for neurosurgical guidance used a relocatable, noninvasive technique to accurately combine anatomical and metabolic information for the selection of a target for biopsy. With neuronavigation, the neurosurgical procedure relies directly on the preoperative planning, the choice of the neuroimaging procedure used for planning is of major importance. Metabolic information provided by PET may help to define the tumor residues that affect the patient's prognosis. Neurosurgical planning integrating PET data may optimize the resection of brain tumors directed by neuronavigation, a factor that may ameliorate the prognosis. The management of low grade gliomas are not always advisable or easy to perform because of their infiltrating nature and their possible location in highly functioning regions. An area of high FDG uptake in low grade gliomas is correlated with a poorer prognosis (60).Consequently, if surgery is recommended, it is important to consider the tumor's glucose metabolism and employ neuronavigation guided by PET-FDG. This approach targets the removal of hypermetabolic areas, which can enhance the patient's prognosis.

2.4.5 Intraoperative Ultrasonography

Despite advances in medical imaging techniques and their routine preoperative use, real-time intraoperative information regarding anatomy remains of significant importance to the neurosurgeon. Accurate localization of neurosurgical targets is essential to minimize surgical morbidity and to reach this goal, ultrasound was extensively used in neurosurgical procedures during the last quarter of the twentieth century and the echogenic characteristics of various lesions were defined. Ultrasound's most important advantage is its capability to depict in real time the anatomical characteristics of the surgical field. Furthermore, it does not require radiation, it is easy to use and it is relatively inexpensive (61). With the advent of real-time sector ultrasound scanning, it became possible to actually image various structures in two dimensions within soft tissue. Since the skull remained a barrier to sector scanning, initial brain imaging was performed through the open fontanelles of neonates. This proved to provide excellent brain imaging and has now become a standard technique for identifying hydrocephalus and intraventricular hemorrhages in the newborn (62). Intraoperative US can be used to acquire images of the anatomy and of the vasculature at any time during the operation.

This information, if correlated to the pre-operative data, can be used directly to measure and correct for brain shift. Alteration of the surgical anatomy of the lesion and surrounding structures may be the result of intraoperative displacement of the brain tissue due to surgical retraction or resection of the cavity itself. The combination of neuronavigation systems with data obtained from intraoperative ultrasound has provided the opportunity to partially overcome errors due to tissue movement. Ultrasound has the unique distinction among other imaging modalities of producing real time images. However, images are often difficult to interpret because echogenic structures cannot reliably discern normal from abnormal tissue. Additionally, Blood products in the surgical field may cause misinterpretation of ultrasound images. Intraoperative ultrasound is controlled by a workstation that is attached to a transducer connected to a tracking attachment that tracks the position and orientation of the transducer and reports this information to the workstation. The position of the transducer is then recorded in coordinates with respect to both patient and physical space which are then transferred onto maps created by MRI or CT images (32,32) . To accommodate shifts in anatomical tissues during surgery, it's essential for surgeons to access real-time imaging. Doppler ultrasound (U/S) is one such imaging technique used intraoperatively, although it offers somewhat limited image quality of the brain. These images can be used to update preoperative MR images. The U/S images are directly superimposed on the MR images, allowing surgeons to navigate using these updated visuals. Additionally, newer technologies enable the creation of a 3D U/S volume from multiple 2D U/S images. The U/S probe is equipped with LEDs to track its position relative to a patient reference frame, enabling surgeons to navigate within this 3D volume seamlessly as the U/S image acquisition and navigation occur within the same coordinate system. This setup also allows for the storage of the 3D volume in the navigation system, eliminating the need for the U/S probe to remain within the surgical area, where it could obstruct other surgical instruments (15).

2.4.6 Functional Magnetic Resonance Imaging

The goal of many intracranial neurosurgical procedures is to accurately localize and then completely excise a lesion or region of cerebral cortex without causing any neurological deficit.

One key factor in assessing surgical risk is the proximity of the lesion to critical brain areas, as damage to these "eloquent" regions can lead to irreversible neurological deficits. While general cortical anatomy provides a rough guide to locating these functional areas, individual variations and distortions caused by local pathology complicate precise mapping. To address this, various cortical mapping techniques have been developed to optimize the balance between maximizing tumor resection and minimizing the risk of damaging functional cortex.

Basic neurophysiological studies have shown that there is tight coupling between neuronal activity, blood flow and metabolism (63). As neuronal activity increases in a specific cortical region, regional cerebral blood flow (rCBF) also rises in response to heightened metabolic needs. This phenomenon underpins hemodynamic/metabolic mapping techniques, including activation PET studies and functional MRI (fMRI). For instance, fMRI utilizes changes in rCBF detected through the contrast bolus tracking technique, which tracks signal changes in the cortex following a galodium injection. Additionally, the blood oxygenation level dependent (BOLD) technique uses the natural paramagnetic properties of deoxyhemoglobin as an endogenous contrast agent, providing a noninvasive method to assess rCBF changes linked to neuronal activity, making it a preferred method in fMRI.

To obtain fMR images for clinical use requires special imaging acquisition sequences where a variety of tasks can be carried out, depending on the requirements of the clinical situation followed by detailed computer image analysis of processing detailed image, coregistration and rendering. The structural and functional model of the individual’s brain is created and the concurrent three-dimensional rendering of cerebral topography, cortical veins and related pathology gives an unprecedented display of critical relational anatomy. This kind of information can be extremely useful in planning and carrying out cortical resections of all types. It is especially useful in resecting tumors because the location and subcortical extent of the lesion can be appreciated. fMR imaging can be used noninvasively to localize cortical sensorimotor and language function which is extremely useful for both operative planning and intraoperative decision making (64). Preoperatively, the fMR images can be used to determine the feasibility of open surgical approaches and to determine those areas of cortex that might be at risk in the planned surgical procedure hence, a more accurate individualized assessment of risk relative to the planned surgical procedure can be formulated.

Intraoperatively, three-dimensional representations of lesions with respect to critical functional areas provide essential information to the operating surgeon. ROIs can be superimposed on the patient’s soft tissue/scalp rendering and their locations with respect to normal anatomical landmarks can be seen, measured and used to plan scalp incisions and bone removal. Once the dura is openedm the fMR images display gyral anatomy, superficial veins and functional areas. An accurate anatomical representation of these areas with respect to one another can be a valuable tool in identifying the exact location and extent of subcortical lesion as we; as in planning cortical incisions/trajectories and resection margins. As the brain shifts after withdrawal of CSF following administration of mannitol or during the resectioning of a tumor, the veins shift along with the cerebral structure and the relative anatomy of the veins to the functional areas or lesions is preserved.

2.4.7 Diffuse Tensor Imaging

Diffusion tensor imaging (DTI) is a recent technique that utilizes diffusion of water molecules to make assumptions about white matter tract architecture of the brain. Early on, neurosurgeons recognized its potential value in neurosurgical planning, as it is the only technique that offers the possibility for in vivo visualization of white matter tracts (65). DTI is a tool that contributes to achieve the goal of maximal resection while minimizing loss of neurological function during brain tumor surgery. The first practical implementation was the integration of the pyramidal tracts, estimated with diffusion weighted imaging, in a neuronavigation system (66).

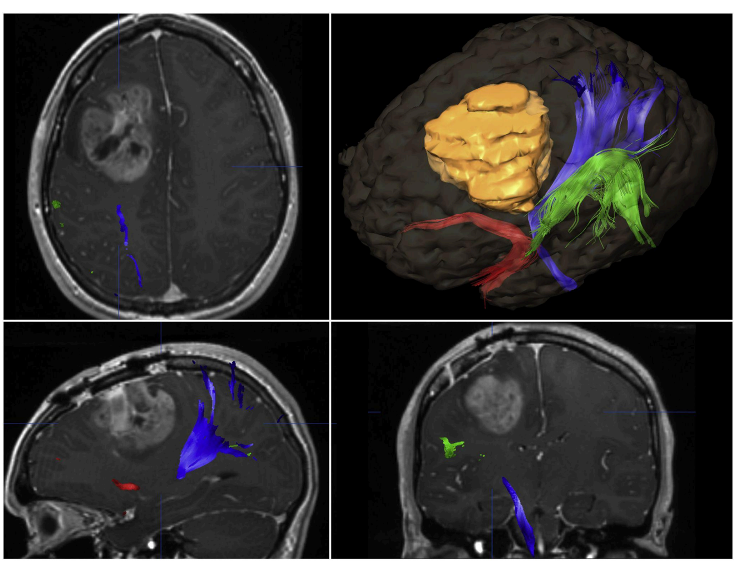


Figure 12. White matter tractography presenting with left frontal glioblastoma. Observe relationship between the tumor (orange) and eloquent tracts (green: arcuate fasciculus, red: uncinate fasciculus, blue: corticospinal tract), These results are valuable for planning the safest surgical route and resection. Walid I. Essayed, Fan Zhang, Prashin Unadkat, G. Rees Cosgrove, Alexandra J. Golby, Lauren J. O'Donnell, White matter tractography for neurosurgical planning: A topography-based review of the current state of the art

The in vivo quantification of water molecular diffusion using magnetic resonance imaging (MRI) was first reported in 1986. Diffusion refers to the random thermal movement, also known as Brownian motion. In biological tissues, diffusion is often not purely random due to the presence of barriers that restrict movement in certain directions. When water molecules move freely in all directions, it is termed isotropic diffusion. Conversely, when movement is restricted along one axis, it is known as anisotropic diffusion. The observed diffusion process is influenced by the applied magnetic gradients and the orientation of myelinated white matter tracts. The exact mechanisms underlying this anisotropy in white matter tracts remain unclear. With DTI it is possible to use anisotropy to analyze axonal organization of the brain. This is based on the concept of diffusion in different axes (67). Tracking white matter tracts is based on MRI-detection of molecular motion of tissue water. In highly structured tissue, such as cerebral white matter, water molecule diffusion is restricted in the direction perpendicular to the fibers, due to cell membranes and myelin sheaths, whereas it is relatively unrestricted in the direction parallel to the fibers, i.e. it shows an anisotropic pattern. The water molecule diffusion within a voxel can be conceptualized as an ellipsoid shaped tensor. The directions of the three main axes of the ellipsoid represent the eigenvectors, their magnitude and the eigenvalue of the tensor (68). Intraoperative acquisition of DT-MRI and fMRI is not practical, due to long scanning and imaging processing times. On the other hand, the use of image data acquired in advance for neuronavigation is limited by brain shift (68). A potential solution to this issue involves utilizing robust biomechanical simulation algorithms alongside intraoperative conventional MRI. This approach helps maintain the accuracy of preoperatively acquired functional MRI and diffusion tensor MRI data (69). In the presence of a tumor, white matter can be displaced, disrupted, edematous or infiltrated by the tumor. DTI can illustrate the local effects on white matter integrity, typically described in four patterns: 1. normal signal with altered position/direction indicating tract displacement; 2. decreased signal with normal direction/location suggesting vasogenic edema; 3. Decreased signal with disrupted fiber tracts indicating tumor infiltration; and 4. Loss of anisotropic signal indicating tract destruction (70).

DTI, when used with other imaging modalities, enhances presurgical and intraoperative guidance, improving the safety and specificity of neurosurgical procedures, especially in anatomically distorted regions. Integration of DTI and fMRI into neurosurgical navigation systems offers patient-specific guidance, increasing the efficacy and safety of tumor resections.

2.5 Current state of Image Guided Neurosurgery

Over the past twenty years, intraoperative image guidance has been utilized across various surgical fields to pinpoint subsurface targets that are not directly visible. While significant progress has been made, traditional navigation techniques still require surgeons to mentally convert two-dimensional images from scans like CT or MRI into three-dimensional anatomy. Additionally, they must relate this 3D digital anatomy back to the patient during surgery, often while using instruments and viewing a separate display. Modern imaging techniques in image-guided neurosurgery have evolved significantly, enhancing precision in surgical interventions. Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) remain pivotal, with innovations like Diffusion-Weighted Imaging (DWI) and functional MRI (fMRI) improving tumor and neural tract visualization. Intraoperative imaging technologies such as intraoperative MRI (iMRI) and CT provide real-time guidance, crucial for tasks like tumor resection and managing cerebrovascular incidents. These advancements have led to better surgical outcomes by allowing more accurate and safer interventions.

Neuroimaging in neuro-oncology includes diagnosis, neuronavigation, and monitoring treatment response (71). Before surgery, MRI is essential for pinpointing the tumor's location, surrounding structures, and characteristics such as edema, which aids in grading the tumor and forecasting outcomes. This preoperative imaging is crucial for planning the surgical approach to maximize tumor removal while preserving vital brain tissue. It also helps determine the best positioning for the patient, the optimal size and location of the craniotomy, and the safest surgical trajectory. Importantly, neuroimaging like functional MRI (fMRI) identifies critical areas, such as the motor cortex, to help avoid postoperative functional deficits by planning around these regions. During surgery, neuroimaging is integrated for neuronavigation by combining preoperative images with real-time surgical positioning. An example of such integration involves a fixed reference frame on the operating table with infrared cameras tracking surgical tools. These tools are then visually represented in real-time on the preoperative neuroimaging of the patient, providing dynamic intraoperative guidance. This system allows surgeons to see the precise location of surgical instruments in relation to the patient's anatomy and imaging data. Brain tumors can alter vascularity based on tumor-induced angiogenesis and this can be measured using imaging techniques including perfusion-weighted MRI, dynamic contrast enhanced MRI and dynamic susceptibility contrast MRI (71). Furthermore, computational model neuroimaging-based techniques can help perform non-invasive diagnostics. Diffusion tensor imaging (DTI) allows for non-invasive identification of neural tracts such as corticospinal tract or Meyer’s loop to avoid postoperative motor and visual field deficits. Novel tractography algorithms allow for localization of eloquent white matter tracts despite traditionally confounding effects of localized tumor edema.

In cases of cerebrovascular surgery that includes treatment of arteriovenous malformations, intracranial hemorrhages (ICH), strokes, aneurysms and other vascular lesions with high rates of mortality and morbidity, the most frequently used modality id CT. CT allows quick evaluation of the size and location of ICH, in presence of intraventricular hemorrhage, hydrocephalus and edema. CT angiography (CTA) can localize pathology and may aid prognostication. Intraoperative digital subtraction angiography (iDSA) is infrequently used in open cerebrovascular surgery, yet it has been shown to impact treatment decisions in 12% of cases. iDSA can also diminish the need for unnecessary surgical steps and reduce intraoperative time. When combined with near-infrared indocyanine green video angiography, iDSA enhances the assessment of vascular flow during the resection of vascular lesions, such as cavernomas or arteriovenous malformations, thus improving patient outcomes (72). Overall, imaging plays a crucial role in cerebrovascular surgery, and advancements in neuroimaging techniques are key to enhancing surgical results.

Image-guided neurosurgery (IGNS) for spine surgery is an advanced technique that significantly improves the precision and safety of spinal operations. Employing real-time imaging technologies like MRI or CT scans, IGNS equips surgeons with detailed, three-dimensional visualizations of both the spinal anatomy and the surgical tools in use during the procedure. This guidance enables surgeons to precisely navigate through complex spinal structures, greatly reducing the risk of injury to adjacent tissues and enhancing the overall outcomes of the surgery. Additionally, sophisticated spinal imaging techniques such as MRI and CT provide crucial preoperative insights. For instance, preoperative CT scans are instrumental in evaluating the anatomy of pedicles to facilitate the planning of screw placements in instrumented fusions. CT myelography is useful for assessing the spinal cord, nerve roots, and spinal lining by injecting contrast into the thecal sac. The use of intraoperative x-ray imaging has reduced dependence on anatomical landmarks, allowing surgeons to confirm spinal levels accurately, minimize incidents of surgery at the wrong level, and improve the accuracy of pedicle screw placements. Originally developed for brain surgeries, surgical image guidance technologies have now been adapted for use in spine surgery as well. Systems like StealthStation (Medtronic, Memphis, TN, USA), use a reference arc attached to a fixed spinous process to register 3D data with intraoperative patient position . This allows surgeons to use preoperative image data fused with intraoperative 3D data for patient-specific surgical guidance. Intraoperative imaging, such as O-arm and Airo, allow imaging in an operative position, increasing safety and accuracy. These modern intraoperative neuroimaging systems have revolutionized spine surgery and patient care (73).

Among the various advanced surgical adjuncts being integrated into the operating room, the incorporation of machine technology, such as image guided robotics, into neurosurgery holds the potential to significantly transform the standards, principles and practices of the field. Many advanced imaging technologies have been adapted for therapeutic use in neurosurgical operating rooms. Advanced brain mapping generates three-dimensional preoperative image data for registration and localization, integral to neuro-navigation technology. This fusion and real-time display increase surgical accuracy. These advancements allow surgery to move towards operating within a real-time image, using an intraoperative imaging platform that accounts for brain shift and surgical manipulation effects. This concept includes an image-guided robotic platform for both microsurgery and stereotaxy, enabling telesurgery within an MRI scanner (74,75). Robotic assistance in neurosurgery can be particularly useful for procedures with very confined operative spaces and applications of robots in neurosurgery include anatomical localization, stabilization of the surgeon’s hand, anatomical planning for access to deep brain targets, and pedicle screw placement in spinal procedures (76,77). Neuromate, Pathfinder, NeuroArm, SpineAssist and Renaissance are among the robotic systems commonly used in neurosurgery. There are evidence seen in neurosurgery where the wide adoption in the usage of robotics is lacking despite the rich history of neurosurgical innovation in stereotaxy and brain localization, the highly technical nature of the field and the continued demand for minimally invasive procedures (78). Robotics have numerous applications in neurosurgery, notably in robot-assisted screw placement during spinal surgery, which has been shown to be safe and accurate in multiple studies (79). This method offers advantages over traditional surgery, such as reduced radiation exposure and fewer facet joint violations. Meta-analyses and a randomized control trial indicate superior accuracy and clinical outcomes with robotic assistance compared to the conventional free-hand technique (80). However, high initial and maintenance costs , mathematical literacy requirements and increased space needs pose barriers to widespread adoption and scalability within neurosurgery (78).

Chapter 3

Methodology

3.1 Introduction

This chapter outlines the methodological framework adopted in this thesis to explore the usability, cognitive workload, technical limitations, accuracy issues and scopes associated with image-guided neurosurgery (IGNS) systems as perceived by neurosurgeons. Given the complex nature of IGNS technology and its critical role in enhancing surgical outcomes, a comprehensive understanding of these factors is paramount. The methodology employed is designed to rigorously assess both quantitative and qualitative aspects of IGNS, enabling a holistic evaluation of its current applications and potential areas for improvement.

The research employs a mixed-methods approach, integrating both survey data and subjective assessments to address the overarching research questions. This approach allows for a thorough investigation of the scopes and limitations of IGNS, as reported by the neurosurgeons who use this technology in their clinical practice. By leveraging validated instruments such as the System Usability Scale (SUS) and the NASA Task Load Index (NASA-TLX), along with detailed demographic inquiries and open-ended questions regarding future system expectations, this study aims to capture a comprehensive snapshot of the current state of IGNS.

The importance of this methodology lies in its ability to systematically gather and analyze data that reflect the real-world experiences of neurosurgeons. The insights derived from this research will contribute to the ongoing discourse on the efficacy of IGNS, potentially guiding future technological enhancements and training protocols. Ultimately, this methodological approach not only addresses the specific research questions posed but also underscores the importance of user-centered research in the evolution of neurosurgical practices.

3.2 Research Design

Type of Research Conducted

The research conducted for this thesis is primarily based on survey research, a non-experimental, descriptive research method that involves collecting data directly from subjects through structured questionnaires. The survey encompasses both quantitative elements, such as the System Usability Scale (SUS) and the NASA Task Load Index (NASA-TLX), and qualitative elements, including demographic questions, learning curve assessment and open-ended responses about assessing practical viability of the system and future expectations for image-guided neurosurgery (IGNS) systems.

Justification for using Survey Research Design

- Feasibility and Efficiency: Survey research is particularly well suited for studies that need to gather data from a relatively large group of respondents within a manageable timeframe and budget. Given the scope of the thesis which aims to assess perspectives from a broad sample of neurosurgeons, this method allows for efficient data collection and analysis.
- Quantitative and Qualitative insights: By using a mixed-methods survey approach, the research design enables the capture of both measurable data from scales and indices, and richer, contextual insights from open-ended questions. This dual approach provides a more nuanced understanding of the usability and cognitive demands of IGNS, as well as the technical challenges and accuracy concerns voiced by practitioners.
- Standardization and Comparability: The use of standardized instruments like System Usability Scale and NASA-TLX ensures that data collected are reliable and can be compared across different respondents. This is crucial in studies like this where assessing and comparing cognitive workloads and suability perceptions across a diverse group of neurosurgeons is essential.
- Flexibility and Scope: Survey research allows the inclusion of a wide range of questions, from fixed-response to open-ended, which is ideal for exploring both the current state and future expectations of IGNS technologies. This flexibility helps in addressing the

comprehensive set of research questions posed in this thesis, covering technical limitations, accuracy issues and overall scopes and limitations of IGNS.

- Assessment of Learning Curves: Understanding how quickly and effectively neurosurgeons can master new technologies is crucial for assessing the practical viability of these systems. The survey includes specific questions and metrics to assess the time and effort required by neurosurgeons to become proficient with IGNS, thereby providing valuable data on the ease of learning and integration into clinical practice.
- Direct Feedback from End- Users: Utilizing a survey that includes neurosurgeons who are the end-users of IGNS provide direct insights into their experiences and perceptions, marking the findings more relevant and actionable for improvement of IGNS technology.

3.3 Participants

Description of Participant Pool

The participant pool for this study consists of neurosurgeons in India who are currently practicing and have experience with image-guided neurosurgery (IGNS) systems. This group was selected to provide insights into the usability, cognitive workload, technical limitations, accuracy issues and future scope associated with the use of IGNS technology in neurosurgical procedures.

Number of Participants

Total number of 44 neurosurgeons have participated in this survey. This sample size was chosen to ensure a diverse representation of experiences and perspectives while remaining manageable for in-depth analysis. The number of participants is adequate to allow for meaningful statistical analysis, facilitating reliable conclusions about the usability, cognitive workload, and technical aspects of image-guided neurosurgery systems among this professional group.

Characteristics of the Participants:

- Professional Status: Participants include a mix of fully licensed neurosurgeons and neurosurgical residents who are at various stages of their training. This diversity allows the study to capture a broad range of experiences and perspectives on IGNS.

- Experience with IGNS: All participants have either used IGNS systems during surgical procedures or have been involved in cases where such systems were utilized. This criterion ensures that all respondents have firsthand knowledge and experience with the technology, providing valuable insights into its practical applications and limitations.
- Institutional Variation: Participants work in a variety of settings, including academic medical centers, community hospitals, and private practices. This range provides perspectives from different institutional contexts, which can affect the availability, usage, and perceived value of IGNS technologies.

3.4 Data Collection Instruments

System Usability Scale (SUS)

The System Usability Scale (SUS) is a widely used standardized questionnaire for the assessment of perceived usability (81). It consists of a 10-item questionnaire with five response options for respondents, ranging from “Strongly disagree” to “Strongly agree”. This scale measures the overall usability of a system, providing insights into how users perceive the ease of use and efficiency of the technology. The SUS is particularly appropriate for this study as it helps quantify the usability of image-guided neurosurgery (IGNS) systems from the perspectives of neurosurgeons, thereby aiding in evaluating how user-friendly and accessible these technologies are. It is also a quick and easy assessment , which is crucial in settings where time is a constraint, such as busy neurosurgeons.

NASA Task Load Index (NASA-TLX)

The NASA Task Load Index is a multi-dimensional rating procedure that provides an overall workload score based on a weighted average of ratings on six subscales : Mental Demands, Physical Demands, Temporal Demands, Performance. Effort and Frustration (82). This tool is relevant for assessing the cognitive load associated with the use of IGNS systems, helping to understand how these technologies affect the mental and physical efforts of neurosurgeons during surgeries. The relevance of NASA-TLX in this research lies in its ability to provide detailed information on the different aspects of cognitive load, which can influence the adoption and efficiency of complex surgical technologies.The tool is relatively easy to administer and interpret, which is crucial in busy clinical environments where time is a constraint. It can be efficiently used in the context of a study without imposing significant additional burden on participants. NASA-TLX has been extensively validated and is widely used in various fields, including healthcare. Its robustness and reliability make it a trusted choice for assessing cognitive load in environments where precision and accuracy are critical, such as in neurosurgery (83).

Learning Curve Assessments

Learning curves were evaluated analyzing the progression of neurosurgeons proficiency with IGNS systems overtime. This was assessed through specific questions regarding the frequency of use, the perceived changes in ease of use, and the time taken to feel competent with the technology. The assessment of learning curves is crucial for understanding the time and practice necessary for neurosurgeons to effectively utilize IGNS systems, which can significantly impact their training and the overall adoption rate of these technologies.

Open-ended Question

The survey included an open ended question designed to gather qualitative data on future expectations for image-guided neurosurgery systems. The question “What are your expectations for future systems?” was asked to capture detailed, subjective insights from neurosurgeons about their hopes, concerns and predictions for the development of IGNS, providing a richer context to the quantitative data collected through other instruments.

3.5 Data Collection Procedure

Methods of Distribution

The data for this study was collected using Google forms distributed via email and Whatsapp to the Neurological Society of India. These methods were chosen to maximize the convenience for participants and to facilitate a higher response rate. The survey invitations and follow-up reminders were sent using the credentials of Dr. Anil Pande, my guide, who is a Senior Consultant Neurosurgeon at various renowned institutions. Utilizing Dr. Pande’s respected credentials helped to lend significant credibility to the survey, thereby encouraging greater participation by reinforcing its importance and relevance to the field of neurosurgery.

Duration of the Data Collection Period

The collection of survey responses was conducted over a period from March 2024 to April 2024. This duration was carefully chosen to allow participants enough time to respond at their convenience, taking into account the demanding schedules typical of neurosurgeons. The two-month window period was also intended to provide ample opportunity for sending out reminders, thus maximizing response rates without unduly prolonging the data collection phase, which could impact the timeline for data analysis and subsequent stages of the thesis.

3.6 Data Analysis

Descriptive Statistics

Descriptive statistics were employed to summarize the demographic data collected through the survey. This included the analysis of:

- Age: Average and range to understand the age distribution of participants.
- Gender: Proportions of different genders to assess gender diversity within the sample.
- Education and Training: Levels of education and specific training in neurosurgery, providing insights into the professional qualifications of the participants.
- Years of Experience in Practice: This helped in understanding the distribution of novice versus experienced surgeons within the group.
- Type of Institution: Whether participants were from academic hospitals, private practices, or other healthcare facilities.
- Geographical Location: Analysis of participants' locations to identify regional trends or biases.
- Role in Practice: Roles such as lead surgeon, consultant, or resident, to gauge the level of responsibility and decision-making power.
- Subspecialty in Neurosurgery: Areas of specialization like pediatric neurosurgery, oncological neurosurgery, etc., to explore specific interests and expertise in the field.

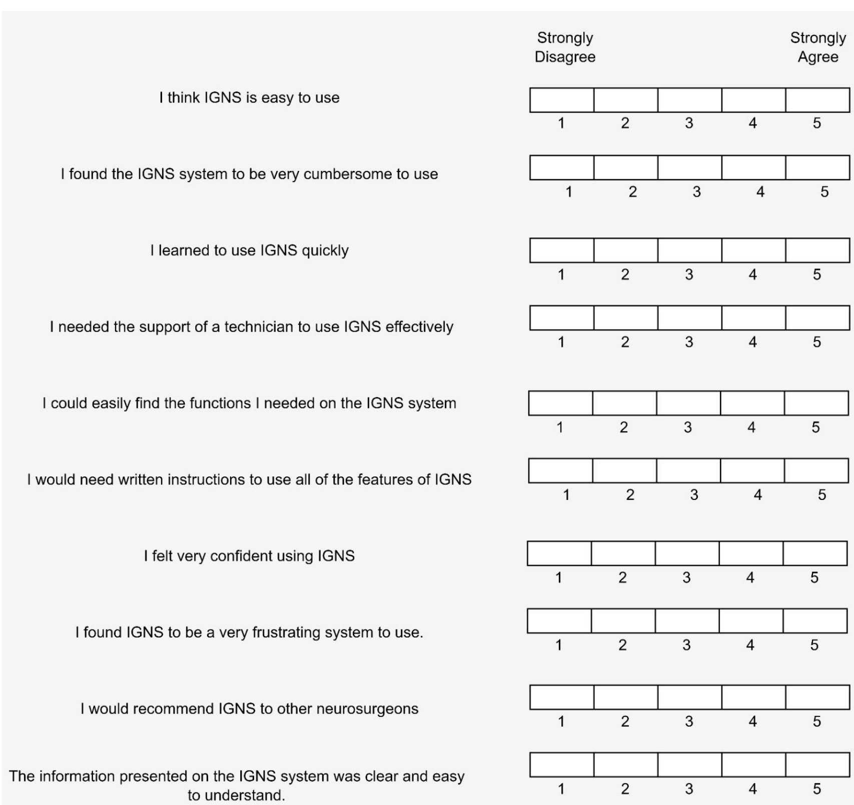
Additional Questions Analysis

Extra questions were analyzed to gather deeper insights into the practical use of IGNS:

1. Types of procedures most commonly performed with IGNS.
2. Factors influencing the decision to use or not use IGNS technology.
3. Frequency of IGNS system usage in surgical procedures.
4. Common types of Image Guided Navigation systems used.
5. Levels of experience with IGNS, identifying common challenges and learning curves.
6. Inaccuracies arising from factors like brain shift during surgery.
7. Strategies used to compensate for such inaccuracies.
8. Limitations of current IGNS in accurately representing patient anatomy.
9. Recommended approaches for managing discrepancies due to brain shift.
10. Integration of IG technology with the surgical workflow.

SUS Score Calculation

The System Usability Scale (SUS) scores were calculated by converting each response to a scale from 1 to 5 , where higher scores indicate better usability. Each item's score contribution was adjusted according to its position in the questionnaire, and the total score was then converted to a scale of 0 to 100 for easier interpretation.



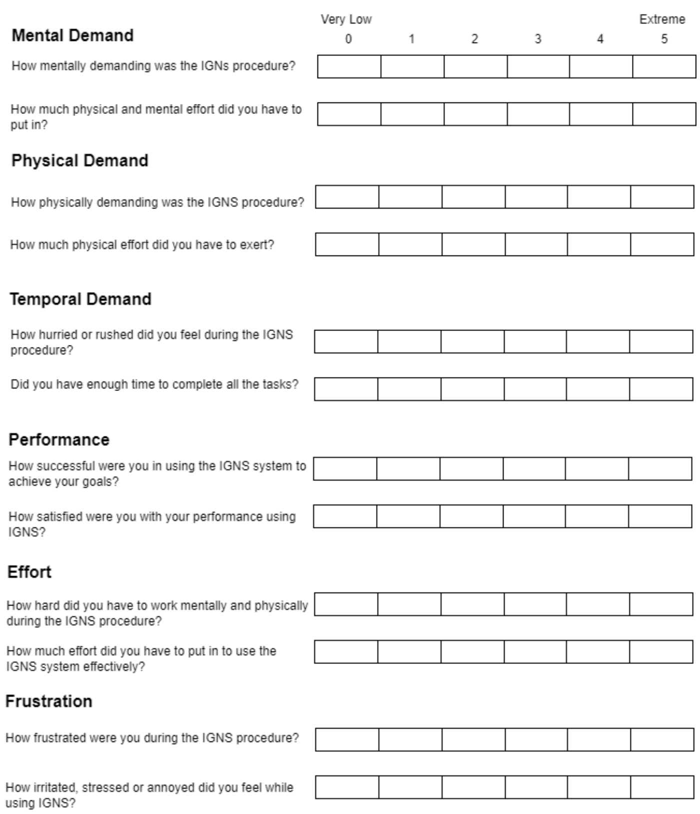
	Strongly Disagree				Strongly Agree
I think IGNS is easy to use	1	2	3	4	5
I found the IGNS system to be very cumbersome to use	1	2	3	4	5
I learned to use IGNS quickly	1	2	3	4	5
I needed the support of a technician to use IGNS effectively	1	2	3	4	5
I could easily find the functions I needed on the IGNS system	1	2	3	4	5
I would need written instructions to use all of the features of IGNS	1	2	3	4	5
I felt very confident using IGNS	1	2	3	4	5
I found IGNS to be a very frustrating system to use.	1	2	3	4	5
I would recommend IGNS to other neurosurgeons	1	2	3	4	5
The information presented on the IGNS system was clear and easy to understand.	1	2	3	4	5

Figure 13. Standard System Usability Scale for survey

To calculate the SUS score, we first take the sum of the score contributions from each response. Each response's score contribution will range from 1 to 5 . For questions with positive connotations, the score contribution is the scale position minus 1. For questions with negative connotations, the contribution is 5 minus the scale position. After which we sum up the overall scores individually and multiply each with 2.5 converting the scoring range from 0-40 to 0-100 The average of SUS scores of all 47 respondents is taken.

NASA- TASK LOAD INDEX CALCULATION

The NASA Task Load Index (NASA-TLX) scores were calculated by having participants rate each of the six dimensions on a scale from 0 to 100. These dimensions include mental, physical, and temporal demands, as well as performance, effort, and frustration.



	Very Low 0	1	2	3	4	Extreme 5
Mental Demand						
How mentally demanding was the IGNs procedure?						
How much physical and mental effort did you have to put in?						
Physical Demand						
How physically demanding was the IGNS procedure?						
How much physical effort did you have to exert?						
Temporal Demand						
How hurried or rushed did you feel during the IGNS procedure?						
Did you have enough time to complete all the tasks?						
Performance						
How successful were you in using the IGNS system to achieve your goals?						
How satisfied were you with your performance using IGNS?						
Effort						
How hard did you have to work mentally and physically during the IGNS procedure?						
How much effort did you have to put in to use the IGNS system effectively?						
Frustration						
How frustrated were you during the IGNS procedure?						
How irritated, stressed or annoyed did you feel while using IGNS?						

Figure 14. NASA- TLX

In the NASA Task Load Index (NASA-TLX) methodology, each dimension is initially rated on a scale from 1 to 5. To standardize these ratings on a scale from 1 to 100, each score is multiplied by 20. For each respondent, the average score across all dimensions is calculated, resulting in an individual NASA-TLX score. To determine the overall workload for the group, the average of these individual scores from all respondents is computed, providing a composite measure of the task's demand.

SPEARMAN'S RHO CORRELATION ANALYSIS

In this study, we employed Spearman's rho correlation analysis to examine the statistical relationship between the System Usability Scale (SUS) and the NASA Task Load Index (NASA-TLX). This method was chosen to determine if the usability of a system correlates with the cognitive and physical workload experienced by its users. Spearman's rho is a non-parametric measure of rank correlation, particularly effective in assessing whether a relationship between two variables can be described through a monotonic function.

This approach is especially pertinent for evaluating SUS and NASA-TLX for several key reasons:

1. Non-Parametric Test: Spearman's rho does not require the assumption of normal distribution of the data, which is beneficial as the normalcy of data distributions cannot always be guaranteed. This is particularly relevant for survey data like SUS and NASA-TLX responses, which may exhibit skewness or non-linear distributions.
2. Suitability for Ordinal Data: Given that both SUS and NASA-TLX scores are ordinal—though numeric—they denote ranked levels of usability and workload, respectively. Spearman's rho is optimal for such data as it focuses on the rank orders rather than the numerical values themselves.
3. Robustness to Outliers: Spearman's rho offers robustness against outliers. Since the method evaluates ranks instead of actual numerical values, extreme scores have a less pronounced impact on the correlation result.

This analytical approach ensures a rigorous evaluation of the interdependencies between system usability and user workload.

APPLICATION:

1. Rank Conversion: Each set of data, encompassing both SUS and NASA-TLX scores, is transformed into ranks. The highest scores are assigned the highest ranks, and scores that are identical receive the average of the ranks they encompass.

2. Calculating the Correlation Coefficient:
    - For each survey response, the difference between the ranks of the corresponding SUS and NASA-TLX scores is calculated.
    - These differences are then squared and summed.

$$\rho = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)}$$

ρ = Spearman's rank correlation coefficient

d_i = difference between the two ranks of each observation

n = number of observations

3. Interpreting the Rho Value:
    - A rho value close to +1 suggests a strong positive correlation, indicating that as SUS scores increase, NASA-TLX scores also tend to increase.
    - A rho value close to -1 implies a strong negative correlation, where higher SUS scores correspond to lower NASA-TLX scores.
    - A rho value around 0 indicates a lack of correlation between the scores.

Computational Tools:

The analysis was conducted using the Python programming language, utilizing the SciPy library to facilitate the computation of Spearman's rho.

LEARNING CURVE ASSESSMENT:

This section of the methodology outlines the approach used to evaluate the learning curve associated with the use of Image-Guided Neurosurgery Systems (IGNS). Understanding the learning curve is crucial for identifying the training needs and challenges faced by neurosurgeons as they adopt new technological tools.

Data Collection Instruments

The learning curve was assessed through a series of structured questions included in the survey, designed to capture both quantitative and qualitative aspects of learning:

1. Time to Familiarity: Participants were asked, "How long did it take you to become familiar with the basic functions of the IGNS system?" This question aimed to measure the initial ease of use and the intuitive nature of the system. Response options ranged from "less than a month" to "more than 12 months."
2. Time to Proficiency: To gauge the depth of learning, respondents answered the question, "How long did it take you to feel proficient in using the IGNS system during surgeries?" Options provided ranged from "less than 3 months" to "more than 2 years."
3. Effective Training Modalities: To identify the most beneficial training approaches, the question asked was, "Which types of training were most beneficial for learning to use the IGNS system?" Multiple responses were allowed, including formal in-person training, online courses, hands-on practice, mentorship, and self-guided learning.
4. Confidence Over Time: Participants responded to, "How has your confidence in using the IGNS system changed over time?" to assess how familiarity and proficiency impacted their confidence.
5. Challenges Encountered: To understand the obstacles in learning, the question posed was, "What were the biggest challenges while learning to use the IGNS system?" This allowed identification of areas where additional support might be needed.
6. Role of Collaboration: The survey included, "How helpful was collaboration with peers or colleagues in overcoming the learning curve?" to evaluate the impact of peer support on learning.

QUALITATIVE ANALYSIS

In this study, we conducted a qualitative analysis of the responses to the open-ended survey question,”what are your future system expectations?”. The goal was to gather insights into the specific improvements and features that neurosurgeons desire in future image-guided neurosurgery systems. The steps taken to analyze these responses were designed to ensure a thorough and systematic examination of the data.

Responses were collected from neurosurgeons as part of a broader survey and transcribed verbatim to facilitate a detailed analysis. The organized data underwent a preparatory phase where responses were read through to gain initial insights and identify potential patterns or themes. Each response was then carefully examined, and meaningful phrases or sentences were annotated with descriptive codes that closely aligned with the data. These codes were grouped into potential themes by combining similar concepts, reflecting broader discussions among the respondents. Each theme was defined and named to precisely reflect its underlying concept, with detailed descriptions that outlined its relevance to the research questions. The final step in the analysis involved selecting illustrative quotes to highlight each theme and integrating these findings into the broader context of existing literature and the study’s objectives.

This process resulted in a structured presentation of the themes, offering a coherent narrative of the neurosurgeons' expectations for future systems and enabled a detailed understanding of neurosurgeons’ expectations for future advancements in image-guided neurosurgery systems, essential for guiding future technological developments.

3.7 Limitations

Limited Number of Respondents

One significant limitation of this study is the relatively small number of respondents. With only 44 neurosurgeons participating, the sample size may not adequately represent the broader neurosurgical community. This limitation can affect the generalizability of the findings, as the responses may not capture the full range of experiences and opinions that exist within the field. The small sample size also limits the statistical power of the analyses, potentially affecting the robustness of the conclusions drawn from the data.

Demographic Diversity Limitations

Another key limitation concerns demographic diversity, particularly the geographical representation of the participants, which was predominantly from urban centers. This urban bias might skew the insights, as neurosurgeons working in rural areas may face different challenges and may have different needs and perspectives regarding image-guided neurosurgery systems. Rural practitioners might encounter issues such as fewer resources, different patient demographics, or logistical challenges that are not as prevalent in urban settings. The lack of rural representation thus limits the study's ability to fully address and understand the scopes and limitations of image-guided neurosurgery across different practice environments.

These limitations are carefully considered when interpreting the results of the study. Future research could benefit from a larger and more geographically diverse sample that includes a balanced mix of urban and rural neurosurgeons to enhance the validity and applicability of the findings across different settings.

Chapter 4

Results and Discussion

This chapter presents the findings from the survey conducted among 44 neurosurgeons regarding their experiences and perceptions of image-guided neurosurgery (IGNS) systems. The results are organized into several sections, each corresponding to the different areas of focus identified in the survey: Demographics, usability, cognitive workload, technological integration, and cost-effectiveness. The findings also include responses to open-ended questions aimed at identifying future expectations for IGNS technologies.

4.1 Descriptive Statistics

4.1.1 Age and Gender Distribution

The age distribution of the 44 respondents ranged from under 30 to above 65 years, with the majority falling within the 35 - 45 age group. This indicates a relatively young cohort of neurosurgeons who are likely to be early to mid-career professionals.

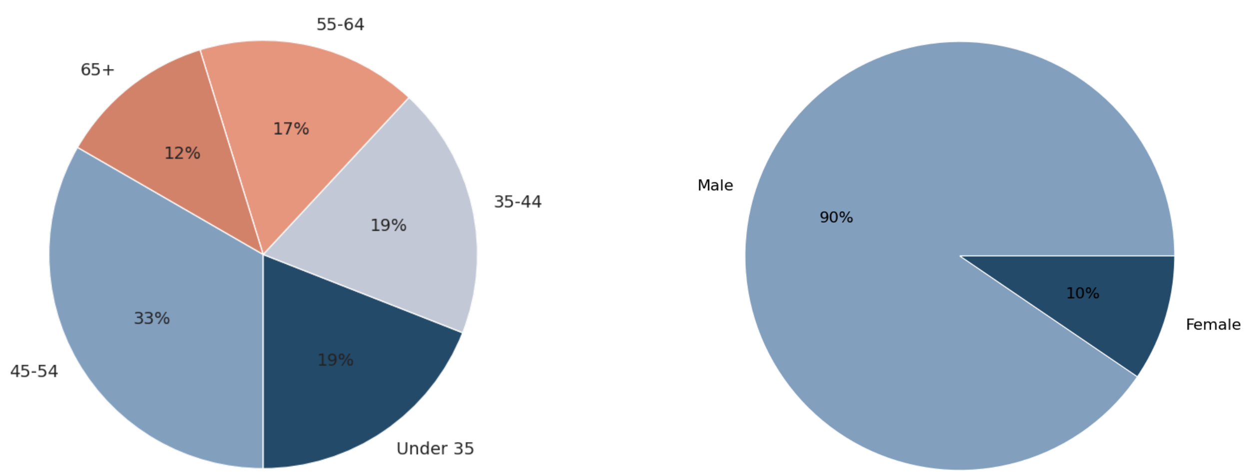


Figure 15. Age distribution of respondents (left) and Gender of respondents (right)

4.1.3 Subspecialty Within Neurosurgery

Respondents specialized in various subspecialities, with the most common being Neuro-oncology, general neurosurgery and spine surgery

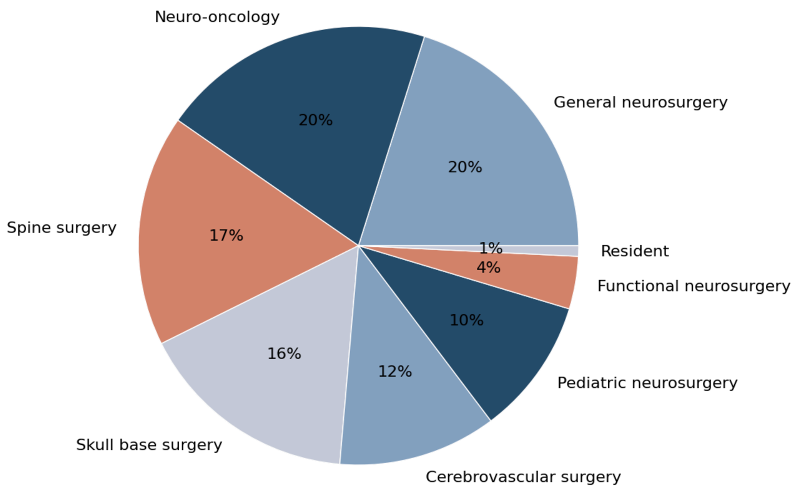
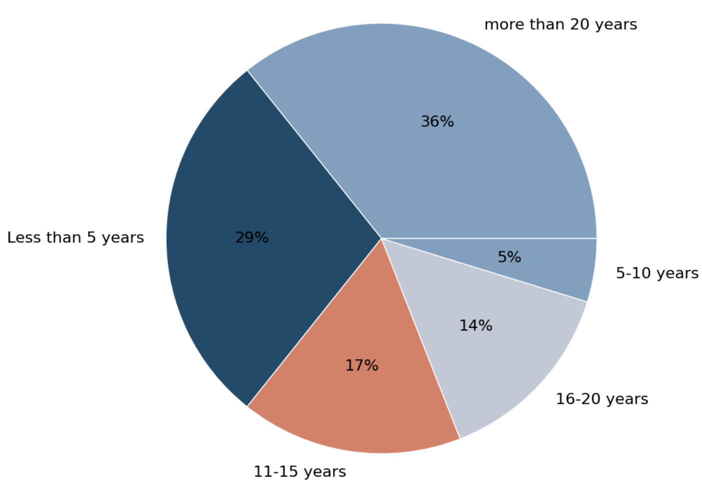


Figure 16. Subspecialty of respondents in neurosurgery

4.1.4 Years of Experience in Neurosurgery and Level of Experience with Image Guided Neurosurgery

The majority of respondents had more than 20 years of experience using IGNS, indicating a well experienced group in the application of this technology



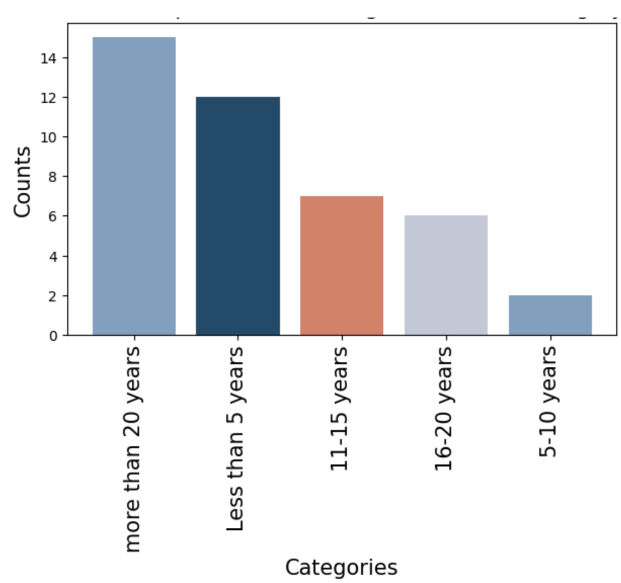


Figure 17. Years of experience in neurosurgery (left) and Level of experience with IGNS (right) of the respondents

4.1.5 Types of Institutes and Geographical Location

The majority of respondents are employed in private hospitals and academic medical centers with a higher concentration in urban areas. Private hospitals and academic medical centers have higher financial resources, enabling them to invest in IGNS (84), The high initial investment and maintenance costs of IGNS systems create a significant barrier for underfunded institutions, widening the gap in the quality of care provided.

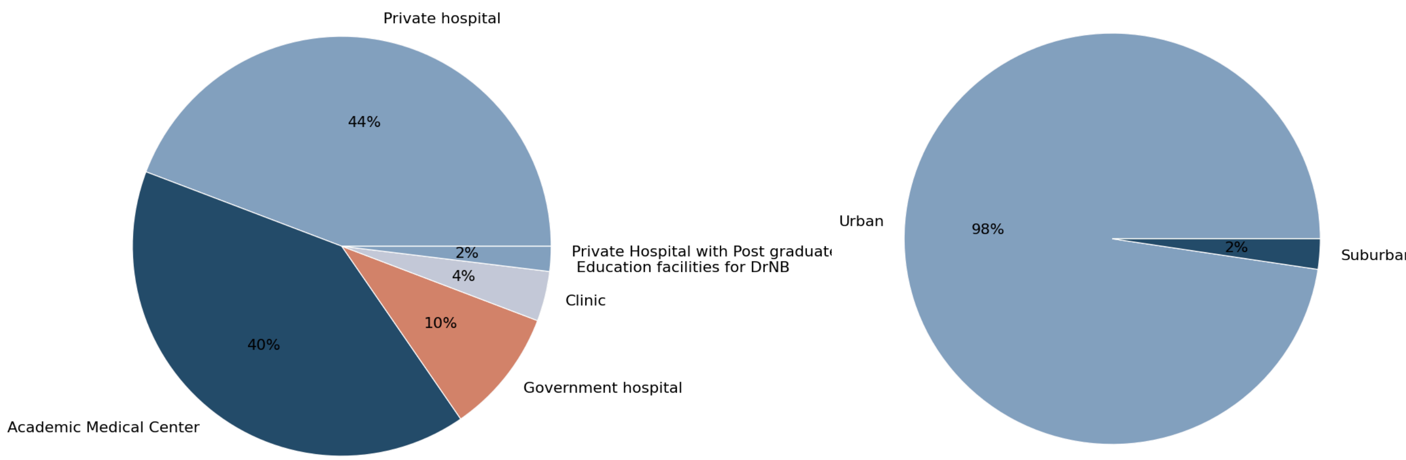


Figure 18. Types of institutes (left). Geographical location (right).

4.1.6 Usage and Experience with IGNS

IGNS is used in more than 75 % of surgeries indicating high adoption of this technology, most frequently used in brain tumor resection and spinal surgery

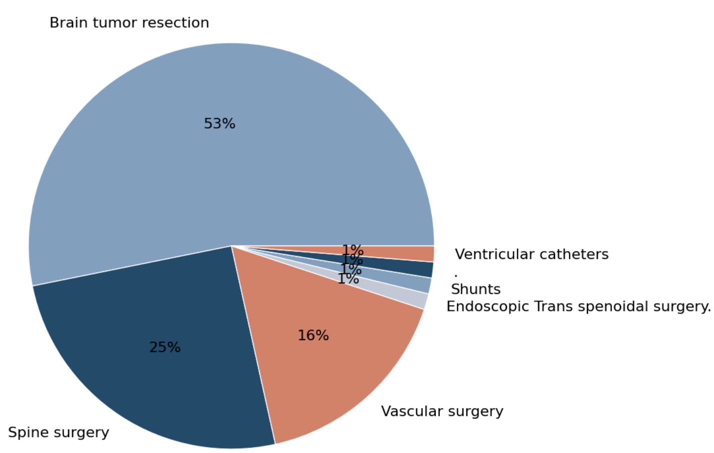


Figure 19. Types of surgery done using IGNS

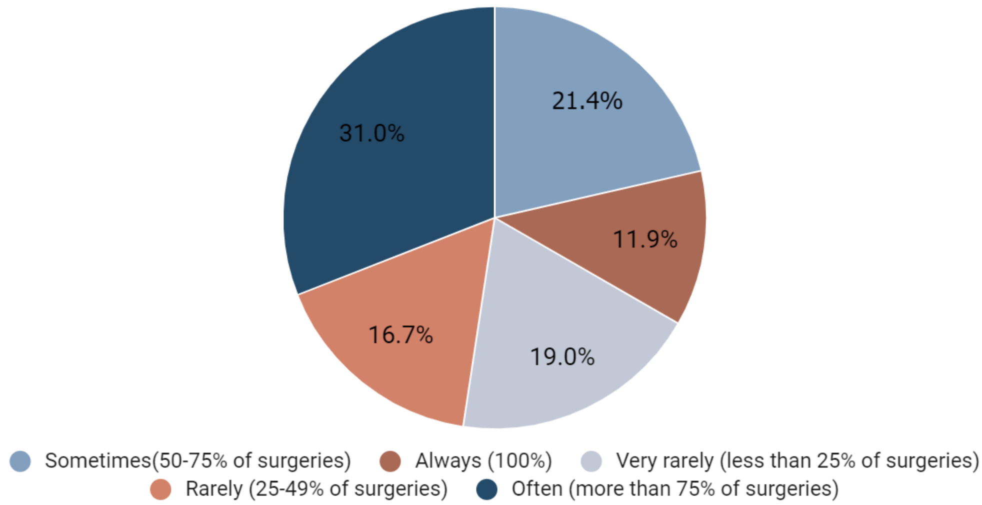


Figure 20. Frequency IGNS usage

4.1.7 Type of Image Guided Navigation system most often used

The most commonly used IGNS is seen to be Medtroics and BrainLab

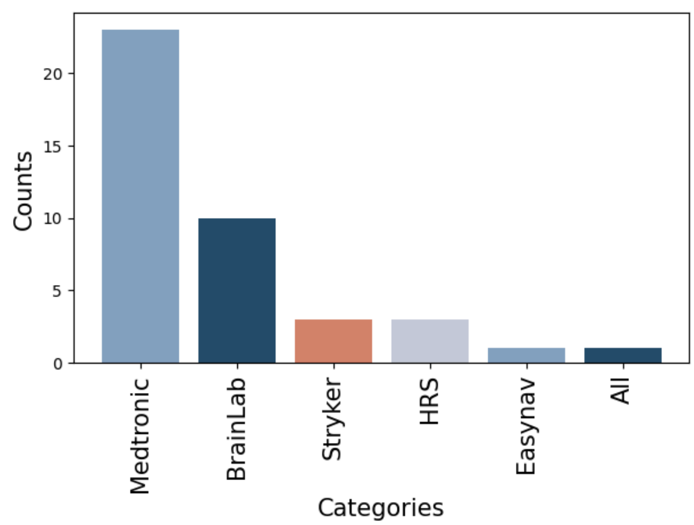


Figure 21. Type of Image guided Navigation system most often used.

4.1.8 Factors influencing decision to use IGNS technology

The factor ‘Precision required for the surgery’ is the most influential with the highest count of responses. Neurosurgeons prioritize IGNS technology when high precision is essential for the success of the surgery. This reflects the value placed on accuracy and minimizing errors in critical procedures. Availability and evidence-based benefits also play significant roles. Ensuring access to IGNS technology and providing adequate training to increase familiarity can further enhance its adoption, leading to more precise and effective neurosurgical outcomes.

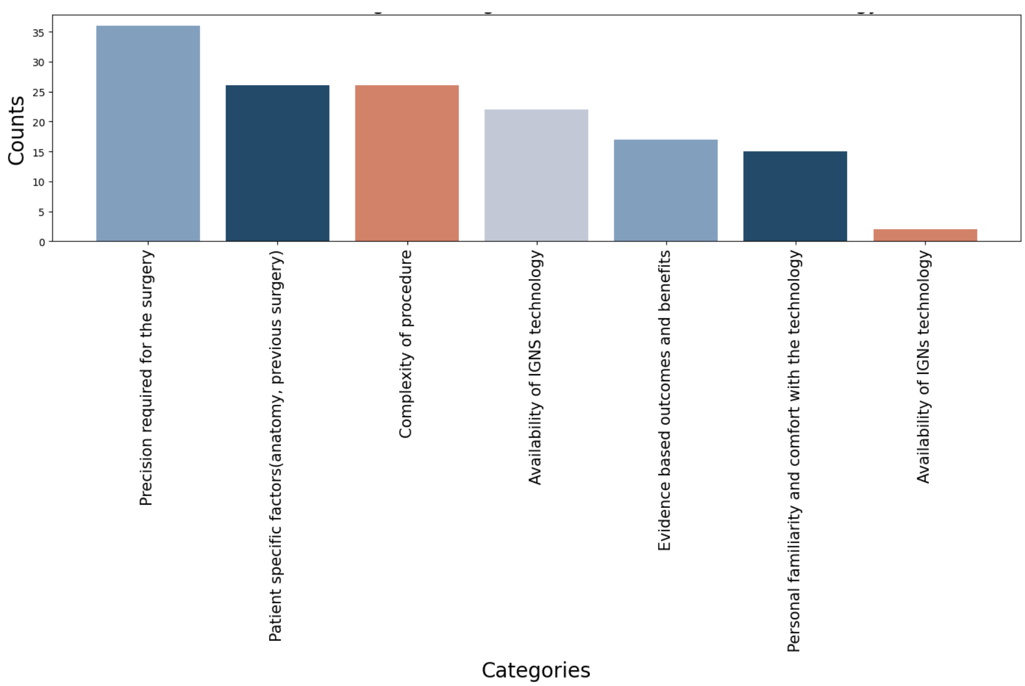


Figure 22. Factors influencing decision to used IGNS technology

4.2 Survey responses

The results from the System Usability Scale (SUS) and NASA Task Load Index (NASA-TLX) provided quantitative data on usability and cognitive load:

- **System Usability Scale (SUS) Result**

  The average System Usability Scale (SUS) score obtained from the survey was **67.5**. The SUS provides a straightforward metric representing the overall usability of a system, where scores are scaled from 0 to 100, with higher scores indicating better usability.

  Interpretation:

  - Scores above 68 are generally considered above average, indicating good usability.

- Scores below 68 often suggest that improvements are necessary, particularly in environments where high usability is critical, such as neurosurgery.

  Thus, with an average score of 67.5, our results position the usability of the current image-guided neurosurgery systems as marginally below average. This suggests that while the systems are functional, there are notable areas that could be optimized to enhance user interaction and satisfaction. This level of usability may indicate that users find the system manageable but possibly not as intuitive or efficient as it could be in a high-stakes medical setting.

  These findings highlight an opportunity for targeted improvements to elevate the user experience, potentially leading to better adoption rates and more effective use of the technology in clinical practice.

- **NASA Task Load Index (NASA-TLX) Result**

  The NASA Task Load Index (NASA-TLX) score for the survey was recorded at 57, which quantifies the perceived workload associated with using the image-guided neurosurgery systems. This score reflects an aggregate measure of various workload factors, including mental, physical, and temporal demands, as well as user's performance, effort, and the level of frustration experienced.

  A score of 57 is considered moderate, suggesting that while the image-guided neurosurgery systems require a significant level of engagement from the user, the demands are not overwhelming. It indicates that the workload, though noticeable, remains within manageable levels for most users. This moderate score implies that the system poses enough of a challenge to be engaging but not so much as to deter efficient usage.

  This level of cognitive workload suggests that improvements can be made to the system to reduce effort and enhance user performance, potentially making the technology more intuitive and less stressful to operate. Such enhancements could lead to more widespread adoption and greater satisfaction among neurosurgeons.

4.3 Spearman's Rho Correlation Analysis

The Spearman's Rho Correlation Coefficient obtained from the analysis was **-0.59**, indicating a moderate to strong negative correlation between the System Usability Scale (SUS) scores and the NASA Task Load Index (NASA-TLX) scores.

Interpretation of the Correlation Coefficient:

Negative Correlation: The negative sign of the correlation coefficient signifies that as the SUS score (which measures usability) increases, the NASA-TLX score (which measures workload) tends to decrease. This relationship suggests that improvements in the usability of the image-guided neurosurgery systems are linked to reductions in the cognitive and physical workload experienced by neurosurgeons. In practical terms, this implies that more user-friendly systems help reduce the stress and effort required to operate them, potentially enhancing overall surgical performance.

Strength of Correlation: The coefficient value of -0.59 is considered to reflect a moderate to strong relationship. This significant correlation underscores the importance of usability in affecting workload levels. It also indicates that while usability plays a critical role in influencing workload, other factors might also contribute to the overall workload experienced by users, suggesting areas for further investigation and improvement in the system design.

This correlation provides valuable insights into how user interface and interaction design directly impact the operational efficiency and comfort of neurosurgeons using image-guided systems. The findings support the need for continued emphasis on enhancing usability to reduce workload, thereby improving the practical utility and adoption of these advanced surgical technologies. More experienced surgeons tended to use IGNS more frequently and rated these systems higher on usability and effectiveness, suggesting that familiarity may play a role in acceptance and satisfaction.

4.4 Learning Curve Assessment

Familiarity and Proficiency with the IGNS System:

The survey results provide insightful data regarding the learning curve associated with the Image-Guided Neurosurgery System (IGNS). Responses indicated a relatively quick adaptation to the basic functions of the IGNS system, with 45% of the participants becoming familiar within less than a month, and 30% within 1-3 months. However, achieving proficiency in using the system during surgeries took slightly longer, with 52.5% feeling proficient in less than three months, and a notable 25% requiring 3-6 months.

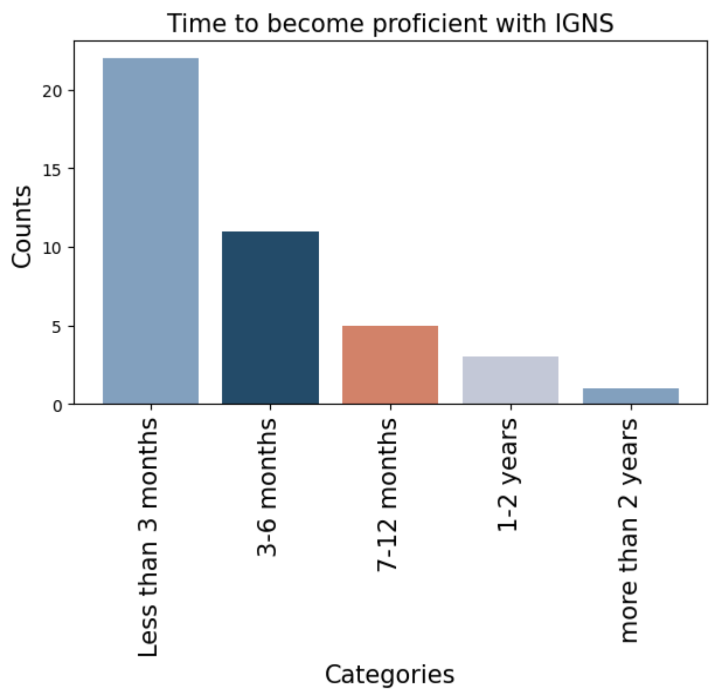


Figure 23. Learning curve assessment : Time taken to become proficient with IGNS

Training Methods and Their Effectiveness:

In terms of training, hands-on practice in the operating room was highlighted as the most beneficial, with 90% of the respondents endorsing it. Other effective methods included formal in-person training sessions (50%), mentorship or shadowing (30%), and self-guided learning through manuals and online resources (25%). The varied responses underline the importance of practical experience and direct guidance in mastering complex medical systems like IGNS.

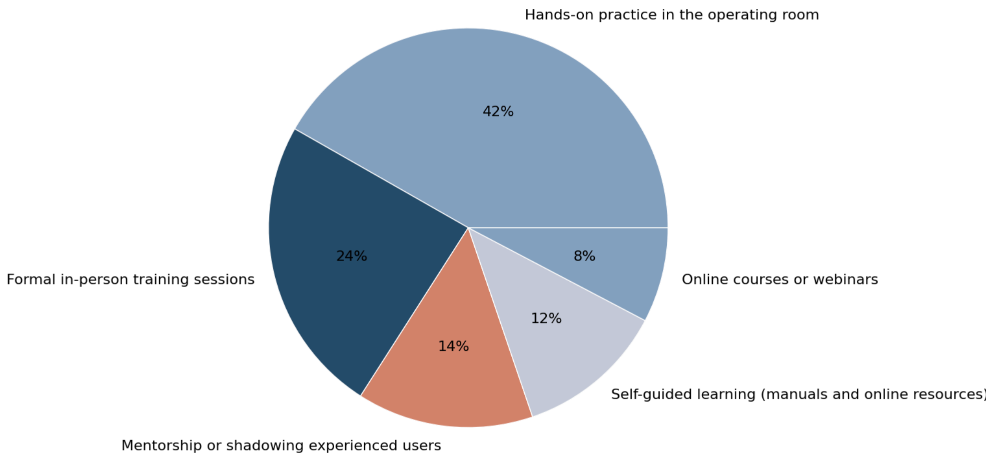


Figure 24. Types of training most beneficial for learning

Confidence and Challenges:

Over time, confidence in using the IGNS system significantly increased for 65% of the neurosurgeons, with an additional 25% reporting a somewhat increased confidence. The biggest challenges identified were handling unexpected issues or malfunctions (67.5%), integrating the system into the surgical workflow (47.5%), and understanding the software interface (42.5%). These challenges highlight critical areas where additional focus on training and system design could be beneficial.

Collaborative Learning:

Collaboration with peers or colleagues was deemed extremely helpful by 50% of the participants in overcoming the learning curve, emphasizing the role of community and shared knowledge in navigating complex new technologies effectively.

Summary of Findings

The learning curve for IGNS is characterized by a relatively rapid initial adaptation followed by a longer period required to reach full proficiency, particularly in operational contexts. The training approaches that combine theoretical knowledge with practical, hands-on experience are the most effective. Challenges remain in system integration and reliability, which could be addressed through enhanced training programs and system design improvements.

Collaboration among peers plays a crucial role in facilitating learning and confidence in using advanced surgical systems. These insights into the learning curve are vital for developing targeted interventions to enhance training efficacy and user experience with IGNS systems.

4.5 Responses to Open ended question

Analysis of the open ended question revealed several key areas for future development:

1. **Usability and User Experience**

   Simplification and Learning Curve: Respondents are looking for systems that are easy to use, with a faster learning curve, more user-friendly interfaces, and simpler operation methods. The emphasis is on reducing the complexity and making the technology more accessible to all users, even in smaller centers.

   Interaction and Workflow Integration: Enhanced interaction between the surgeon and the system during procedures, including direct voice guidance, real-time navigation, and better integration with the surgical workflow, are highly desired. There's also a call for smoother methods of changing settings and better anatomical integration.

2. **Technological Advancements**

   Integration with Other Technologies: There is a strong desire for the integration of image-guided systems with other advanced technologies like intraoperative real-time ultrasonography, 3D microscopes (exoscopes), robotics, and navigation systems as a unified unit.

   Artificial Intelligence (AI) and Automation: Increased use of AI for self-corrections, additional equipment for brain and spine navigation, and automation in specific parts of procedures were frequently mentioned. Respondents expect AI to play a significant role in improving accuracy and efficiency.

3. **Cost and Accessibility**

   A major concern is the cost of the systems. Feedback indicates a need for more affordable, cost-effective solutions that do not sacrifice quality or functionality. This includes easy user-replaceable parts and consideration of overall system costs for broader, universal use.

4. **Accuracy and Performance**

   Respondents expect enhancements in the accuracy of procedures, especially in managing brain shift during surgery. There's a strong call for real-time capabilities, including real-time 3D image injection, fast re-registration of images, and more accurate registration protocols.

5. **Compactness and Design**

   Suggestions include making the systems more compact, clutter-free, and less technically problematic. There's also feedback on physical aspects like the need for protective screen guards and improved camera positioning.

6. **Specific Features and Improvements**

   Specific improvements such as easier patient registration, prone registration, and the inclusion of key anatomical landmarks in registration processes were noted. Additionally, the ability to easily calibrate with ultrasound and microscope technologies is a highlighted need.

Summary

The feedback from the survey suggests a clear demand for future image-guided neurosurgery systems to be more user-friendly, technologically advanced, cost-effective, and accurate, with seamless integration into surgical workflows. Surgeons are looking for systems that can be easily learned and used, even in less specialized centers, with the incorporation of AI and real-time capabilities to enhance surgical precision and outcomes.

These insights could guide the development and refinement of next-generation neurosurgical tools, aligning them more closely with the practical and financial realities of the medical field.

Chapter 5

Conclusion

The exploration of IGNS through this thesis has illuminated both the significant advancements and the inherent challenges that shape its current state and future potential. This retrospective analysis, supported by survey responses from neurosurgeons and a thorough review of literature, underscores the transformative impact of IGNS while highlighting areas requiring further development and refinement.

The key findings include technological advancements that show how IGNS has significantly enhanced the precision and safety of neurosurgical procedures by integrating advanced imaging modalities such as CT, MRI and intraoperative ultrasound. These technologies provide real-time, detailed views of brain and spinal structures, enabling more accurate targeting of pathological areas and minimizing damage to surrounding healthy tissues. The use of image-guided robotics and the potential for real-time imaging during surgery represent significant technological strides that could further improve surgical outcomes. The application of IGNS in brain tumor resection , spinal surgery and epilepsy surgery demonstrated its versatility and effectiveness in improving surgical accuracy and patient outcomes. By facilitating the precise localization of lesions and critical structures, IGNS reduces the risk of complications and enhances the overall efficiency of neurosurgical procedures.

The studies done also highlight the challenges and limitations of using IGNS which includes issues such as brain shift and the inability to update images in real-time pose significant challenges. These limitations can affect the accuracy of intraoperative navigation and complicate surgical procedures. The complexity of IGNS systems and the associated high cognitive load can negatively impact surgeon efficiency and increase mental and physical fatigue; these factors underscore the need for more user-friendly interfaces and streamlined operational processes. The initial high and maintenance costs of IGNS systems limit their accessibility, particularly in underfunded institutions creating a gap in quality of care provided across different settings. The need for specialized training programs to ensure proficiency in using IGNS technology is a critical barrier. Additionally, the mathematical literacy required for operating these systems adds to the cognitive burden on surgeons. Occasional technical failures and system errors can disrupt surgical procedures and pose risks to patient safety. Ensuring the reliability and robustness of IGNS systems is crucial for their effective implementation.

Recommendations for Future Research and Development

Based on the analysis of common usability issues and findings from existing research, several key areas for future research and development in Image-Guided Neurosurgery (IGNS) have been identified. These recommendations aim to enhance the overall effectiveness, usability, and integration of IGNS systems, ensuring they meet the evolving needs of neurosurgeons.

- Enhancement of User Interface
    - Simplified Navigation: Ensure the interface is intuitive, with clear labels and controls to reduce the steps required for common tasks. Simplifying navigation can significantly reduce the cognitive load on surgeons.
    - Consistent Design: Maintain a consistent layout and design language throughout the system to help users predict system behavior and reduce cognitive strain.
    - Customization Options: Allow users to customize the interface according to their preferences and needs, such as adjustable layouts, themes, and the ability to save frequently used settings.
- Training and Support
    - Comprehensive Training Programs: Develop detailed training programs that include hands-on practice, simulations, and mentorship to help surgeons quickly gain proficiency with IGNS systems.
    - Accessible Support Resources: Provide accessible support resources, including online tutorials, quick reference guides, and responsive technical support, to assist users in mastering the technology.
- Feedback Mechanisms
    - Real-Time Feedback: Implement real-time feedback mechanisms that inform surgeons of their actions and the system's responses. This can help users make adjustments during surgery and build confidence in using the technology.

    - Error Prevention and Recovery: Design the system to detect potential errors and provide corrective suggestions, such as confirming actions that could have significant consequences. Clear instructions for recovery from errors should also be provided.
- System Integration
    - Seamless Integration: Ensure that the IGNS system integrates smoothly with other surgical tools and workflows to minimize disruption and streamline the surgical process. This includes automatic data storage of patient details undergoing IGNS and compatibility with a wide range of imaging devices and data formats.
    - Brain Shift Error Detection: Develop predictive models that estimate the extent and direction of brain shift, allowing surgeons to anticipate changes and adapt their approach during surgery.
    - Performance Improvements: Improve the system's performance to reduce lag and ensure smooth operation during critical moments in surgery. Incorporate backup systems and fail-safes to ensure continuous operation even if the primary system fails.
- Involvement of Neurosurgeons
    - Collaborative Design: Involve neurosurgeons in the design and testing phases to gather feedback and ensure the system meets their expectations. An iterative design process can be used to continually refine the system based on user feedback and usability testing results.

By addressing these areas, the future development of IGNS systems can lead to significant improvements in their usability, reliability, and overall effectiveness. These recommendations provide a roadmap for enhancing the capabilities of IGNS technology, ultimately contributing to better surgical outcomes and patient care.

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