Review

Neuronavigation: Image-Guided Neurosurgery

Neuronavegación: neurocirugía guiada por imagen

Abstract

Accuracy is an essential aspect in the performance of brain surgeries that has been the focus of intense clinical research over the history of neurosurgery which have resulted in the development of novel technologies for the localization of intracranial and spinal cord lesions. The advent of new neuroimaging techniques as well as the increasing availability of tools for spatial orientation have improved the ability of neurosurgeons to trace deep brain structures with precision and to perform surgical procedures with the minimum risk. Neuronavigation constitutes a technology incorporated to the neurosurgery practice that allow real-time visualization of tridimensional reconstructions from intracranial structures obtained by preoperative imaging studies on a computer screen, which facilitates the approach to different physiological and anatomical cerebral abnormalities with a higher precision compared with that achieved by other conventional techniques. Its increasing availability forces physicians responsible for the care of patients with neurological disorders potentially candidates for surgery to know the operative technique, principle and applications of neuronavigation as well as advantages and disadvantages offered by such technology for the treatment and prognosis of several cerebral diseases.

Keywords

Neuronavigation, neurosurgery, stereotaxic, cerebral tumors, intraoperatory magnetic resonance imaging.
Resumen

La precisión es un aspecto fundamental en la realización de la cirugía neurológica que ha sido motivo de intensa investigación durante la historia de la neurocirugía y ha resultado en el desarrollo de tecnologías para la localización de lesiones intracranales y de medula espinal. El advenimiento de nuevas técnicas de imagen cerebral, así como la disponibilidad de herramientas de orientación espacial han mejorado la capacidad de los neurocirujanos para acceder con exactitud a estructuras cerebrales profundas y realizar operaciones exitosas con el menor riesgo. La neuronavegación constituye una novedosa tecnología incorporada a la práctica de la neurocirugía y permite una visualización en tiempo real de las estructuras intracranales en un monitor de computadora a partir de reconstrucciones en tercera dimensión obtenidas por estudios de imagen preoperatorios, lo cual facilita el abordaje de diferentes alteraciones fisiológicas y anatómicas cerebrales con una precisión mayor a la lograda por técnicas convencionales. Su creciente disponibilidad obliga a los médicos encargados del cuidado de pacientes con alteraciones neurológicas potencialmente candidatos a cirugía al conocimiento de la técnica, el principio y las aplicaciones de la neuronavegación, así como de las ventajas y desventajas que ofrece dicha tecnología para el tratamiento y pronóstico de diversas enfermedades cerebrales.

Palabras clave
Neuronavegación, neurocirugía, estereotaxia sin marco, tumores cerebrales, resonancia magnética nuclear intraoperatoria.

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Introduction

Have you driven a car in another country or in a different region of your city that you had never visited before? If it were not for technologies such as GPS, you would have surely had to drive around and take wrong turns before reaching your destination. The same thing happens when there is a small brain injury located in a deep region inside the skull. Although most neurosurgeons have sufficient knowledge of the internal structure of the brain as a result of their extensive anatomical knowledge and experience in the surgical field, patients sometimes present alterations that constitute a challenge due to their location, which requires careful planning of the approach and the route to reach the injury.

Precision in the surgical approach has been a preoccupation since the beginning of brain surgery and for many years it has also constituted a continuous research focus for the development of new useful tools for the location of intracranial lesions. This development has always been dependent on the availability of imaging techniques capable of offering an anatomical view of brain tissue, so the advent of new imaging tools has been accompanied simultaneously by improvements in guidance methods and neurosurgical approach. At the beginning, ventriculography (injection of a contrast medium in the ventricular system) was used as a technique to locate and resect lesions near the ventricular cavities that had sufficient volume to deform these structures and thus demonstrate their position with respect to them. Subsequent attempts resulted in the invention of rigid stereotactic reference frames that had originally been used for animal experimentation and were placed around the patient's skull, fixed to it, so that they remained immobile during surgery. The frames contained different systems of Cartesian coordinates that allowed to determine the location of intracerebral structures taking as reference points on the surface of the cranium or in deep sites such as the Turkish seat and the foramen of Monro brought to light by the emergence of radiography and ventriculography, respectively. A historic achievement for medicine and neurosurgery was the invention of sophisticated technologies such as computerized axial tomography (CAT) and nuclear magnetic resonance imaging (NMRI) that allowed obtaining more complete images of cranial bone and brain tissue, as well as their 3D reconstruction from cuts at different brain levels. This was translated into greater precision and better clinical results after the resection of tumors and vascular lesions guided by the use of stereotactic frames that are still in use today given their effectiveness.

However, none of the tools available was able to show in real time the maneuvers performed by the surgeon and superimpose them on the brain images to guide the surgery with precision. In addition, the stereotactic technique had several disadvantages that made the surgical procedure difficult because the reference frame limited the range of maneuver and the visibility was also subject to a high degree of obstruction. Until a few years ago there was no tool that could help the doctor accurately locate different structures inside the skull and perform surgery with minimal risk of damage without the need for a stereotactic frame until image-guided surgery, frameless stereotaxis, or “neuronavigation” was developed.

The first surgery performed with the support of a neuronavigation team was carried out in 1986 by Roberts and his collaborators, using a neuronavigator that superimposed three-dimensional reconstructions of images obtained by CT in the visual field of the microscope, calculating the orientation and position of the latter thanks to a system based on acoustic waves. This technology has had improvements over the past two decades and currently uses information from imaging studies such as CAT or NMRI to upload it to a computerized system in which it is possible to perform three-dimensional reconstructions of brain tissue, superimpose the images of functional studies, and plan the surgical approach. Subsequently, the neuronavigation team integrates spatial
information through optical or electromagnetic sensors that detect and locate different reference points placed on the patient’s skull and whose function is very similar to GPS. It creates a brain map allowing specific points to be located inside the skull, as well as observing the movements of the surgeon superimposed on the brain images in real time or projecting and superimposing the imaging information in the visual field of the microscope. This fact facilitates the planning of the site where the brain will be entered and the structures that will have to be avoided on the way to a lesion or damaged structure without the need to perform a wide craniotomy. For this purpose, the navigation system includes a computerized image processing module, a reference frame or antenna, an optical or electromagnetic detector, and a pointer that is recognized by the detector. (Figure 1)

**Figure 1. Elements that make up the neuro-navigation system.**
The neuro-navigation system consists of a frame of reference or antenna (A) and a pointer (B) and fiducial markers in place (C), which are spheres that reflect the infrared light emitted by the control center (D). The control center is composed of a computer system to which the data of imaging studies are loaded with reconstructions in 3D to display them on a screen, as well as a tower with two light emitters that function at the same time as detectors of the signal reflected by the fiducial markers placed on the pointer and on the antenna. To visualize in real time the position of the surgical instruments on the screen while the surgeon performs the operation, the fiducial markers can also be placed on the instruments (E and F).
Technique

Obtaining brain images
The first step for the procedure is obtaining the brain images to perform a 3D reconstruction. The imaging technique to be used depends on the availability of the resource as well as the precision required for each surgery. In addition, images obtained by different techniques can be superimposed to achieve a reconstruction with the greatest possible anatomical detail. For example, CAT has a greater capacity to evaluate bone structures compared with NMRI, while the latter is superior in obtaining high definition images of soft tissues. The superposition of the information coming from both techniques can provide great detail of the bone tissue and at the same time an optimal image of the cerebral structures. Furthermore, the performance of intravenous contrast imaging techniques such as CT or MR angiography is useful for adding information of cerebral vascular anatomy in the approach of arteriovenous malformations, aneurysms, and other vascular anomalies.

Finally, the increasing availability of functional NMRI and diffusion tensor imaging (DTI) tractography allow locating the eloquent areas and subcortical tracts in such a way that it is possible to superimpose them on anatomical reconstruction and thus plan the surgical approach. For this purpose, neuronavigation can also be combined with cortical mapping by electrostimulation.

Digitization of spatial information by recording anatomical landmarks
To correlate the imaging reconstructions with the spatial information of the patient, the neuronavigation team must obtain coordinates from different reference points located on the skull as well as in several locations within the surgical field and on the instruments that will be used during the surgery. For this purpose, a record of anatomical reference sites is made by placing a pointer on the surface of the skull which has reflecting or fiducial spheres that reflect the ultraviolet light waves emitted by light emitting diodes (LEDs) that are placed in the optical detector which in turn locates the pointer by detecting the light reflected by it. Prior to registration, the pointer must be calibrated by placing its end in the center of a reference point or antenna located in the Mayfield clamp with which the patient’s skull is fixed. The spatial coordinates of each reference site are paired with the 3D reconstructions of the imaging studies and in this way a brain map is constructed that allows the doctor to visualize in the computer the internal structures of the skull while performing the surgery. To facilitate this procedure, individual reference frames or fiducial markers can be used that stick to the surface of the skull and also contain reflecting spheres of light. These fiducial markers are placed before taking the brain images, which improves the accuracy in the pairing of the imaging information with the spatial information. The surgical material and the microscope are also registered, all of which have adapters with reflecting spheres to achieve their location and detection through the optical detection system. When fiducial markers are not available, superficial anatomical structures of the face and skull, such as the tip of the nose, the earlobe, and the inner canthus of the eye can be used to perform the registration.

Update of intraoperative data in real time
One limitation of neuronavigation is its strict dependence on the accuracy of the registration of the reference points and their correlation with the brain images. The displacement of a reference site or the change of position of the cerebral structures imposed by the dissection of the nervous tissue on the way to the target lesion can alter the accuracy of the neuronavigation system. For this reason, different transoperative imaging techniques can be used to update the structural data of the brain. In some developed countries, intraoperative NMRI images are performed, however, this technology requires a sophisticated infrastructure and an economic investment not available in most hospital centers. The third-dimensional ultrasound has also been used to assess brain displacement during surgery,
Figure 1. Procedure for conducting image-guided neurosurgery.

The first step to perform surgery with a neuronavigation system is to obtain the brain images. To facilitate the subsequent pairing of the imaging data with the spatial information, fiducial markers or reflecting beads can be placed on the patient’s skull (A) to serve as reference points and appear in the brain images. The most frequently used studies for this purpose are NMRI and CAT (B), however, functional imaging studies can be performed and these can be superimposed to create a reconstruction in 3D that contains anatomical and functional information (C). Once the brain images are obtained, the spatial information is recorded inside the operating room. For this, the reference frame or antenna and the pointer are used, which indicate the position of the fiducial markers previously placed on the patient’s skull (D). The neuronavigation team matches the position of the spatial reference points with the image data allowing to observe in real time the movements of the surgeon on the screen. Sometimes, an update of the image data is required due to the displacement of the brain structures that may occur after the dissection of the nervous tissue and decompression secondary to the craniotomy. In developed countries, this is done through transoperative NMRI studies (E).
Clinical applications of neuronavigation

Neuronavigation has become an essential tool in the treatment of small and deep brain tumors with poorly defined borders and affecting vascular structures of greater importance. Its main advantage is that it shortens the duration of surgery. In addition, a smaller incision is required on the skull, which translates into a lower risk of infection of the surgical wound, a smaller volume of hemorrhage, and a shorter hospitalization time. In the case of the treatment of brain tumors, it has been observed that its use is of special relevance for the approach and delimitation of the surgical edges in cases of low-grade gliomas, in which it is complicated to define the boundaries between the tumor tissue and normal neural tissue. This is enhanced by the use of preoperative functional imaging techniques. The growing evidence of the relationship between the volume of resection, mortality, and risk of recurrence makes neuronavigation a tool that has a direct impact on the prognosis of patients with brain tumors. However, special care must be taken in the technique because, as mentioned before, intracerebral lesions can deform the nervous tissue locally or the surgeon can move the brain during surgery, which alters the calculations made by the navigation system, so that transoperative images are required to update the data and thus improve the accuracy of the procedure. In addition, in cases of rapidly growing tumors, preoperative images should be taken immediately before performing surgery because, if they are taken too early, inaccuracies and greater difficulty may arise in the correlation of spatial information with image reconstruction.

In addition to the resection of intracranial tumors, neuronavigation has applications in the treatment of different neurological diseases and its accuracy seems to be greater in surgery at the base of the skull because the bony structures are practically immobile. In this way, its use is related to better results in the resection of pituitary tumors since it allows a planning of the surgical approach in greater detail through different bony structures such as the trans-sphenoidal route. Additionally, it allows performing intracerebral biopsies, intracranial endoscopy, and functional neurosurgery with greater accuracy than other conventional techniques thanks to the ability to integrate functional imaging techniques information to achieve the minimum risk of damage to eloquent regions and subcortical tracts. Finally, the use of neuronavigation has, in recent years, grown to address spinal diseases requiring spinal surgery.
Disadvantages

Like all medical intervention, neuronavigation also has some difficulties because it takes a long time to record the reference points and calculations to build the brain map, as well as a surgical field limited in space and visibility. In addition, as already mentioned, intracerebral lesions can deform the nervous tissue locally or the surgeon can move the brain during surgery, which alters the calculations made by the navigation system.¹⁵

A further disadvantage of neuronavigation equipment employing optical ultraviolet light detectors is that the space between the detector and the reference points should be free of obstructions, which is not always possible within the context of a common operating theater. For this reason, there are other devices equipped with magnetic field detectors but their availability is lower.³²

Perhaps the greatest limitation of neuronavigation is the high cost and poor infrastructure of many hospital centers in underdeveloped countries, a fact that must be overcome as clinical studies appear in the literature highlighting its cost-effectiveness and as more specialized centers from first world countries share their experience and technical specifications for the performance of image-guided brain surgeries. In spite of this, hundreds of image-guided neurosurgeries are performed every day around the world given the extensive experience of many treatment centers, which places this tool as an example of the benefit of technological development in health care and that it will undoubtedly be improved as new scientific advances arise in the area of biomedical engineering and imaging techniques.

Finally, it is important to mention that the use of neuronavigation in the teaching of neurosurgery can lead to abuse of its use, limiting the development of surgical skills and the acquisition of anatomical knowledge among new neurosurgeons, so it must be remembered that the only role of this type of technology is to act as a support tool and that its absence should not limit the surgical capacity of the surgeon.
Conclusions

Neuronavigation is a novel technology for conducting image-guided surgeries in which the neurosurgeon can observe in real time the situation of surgical instruments as well as each of the maneuvers superimposed on three-dimensional reconstructions of brain images projected on a computer monitor. Its clinical application has been of special importance in the treatment of intracranial tumors and other neurological diseases potentially treatable by surgery. Knowledge of this technique, of its advantages and disadvantages, can improve the prognosis of many patients eligible for this procedure which will continue to be subject to technical improvements as new scientific advances in the area of biomedical engineering and imaging techniques arise. Although it is not a technology that has been developed recently, its use is still limited to first world countries. However, the increase in its availability in underdeveloped countries could benefit hundreds of patients with lesions difficult to approach and should motivate clinical studies to demonstrate its advantages and cost-effectiveness in the treatment of different neurological diseases.

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Conflicts of interest

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