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Image-guided Stereotactic Neurosurgery: Practices and Pitfalls

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Image-guided neurosurgery (IGN) is a technique for localizing objects of surgical interest within the brain. In the past, its main use was placement of electrodes; however, the advent of computed tomography has led to a rebirth of IGN. Advances in computing techniques and neuroimaging tools allow improved surgical planning and intraoperative information. IGN influences many neurosurgical fields including neuro-oncology, functional disease, and radiosurgery. As development continues, several problems remain to be solved. This article provides a general overview of IGN with a brief discussion of future directions.

Key Words Stereotactic · Neurosurgery · Neuro-image · Pitfall.

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Introduction

Stereotactic neurosurgery (SNS) is a minimally invasive surgical procedure for diagnosis and treatment of brain lesions, that relies on locating targets relative to an external frame of reference. Stereotactic is a compound of "stereo" from the Greek "three-dimensional" and "tactus" from Latin "to touch" (1). The object of stereotactic surgery is to actually touch the targeted structure by moving electrodes or probes along three axes, anterior-posterior (AP), lateral, and vertical planes. Since Ernest A. Spiegel and Henry T. Wycis developed the first stereotactic human apparatus in 1947, surgical instruments have advanced along with neuroimaging technology and neurophysiology (2). Compared to other surgical fields, brain surgery limits the acquisition of anatomical information by vision or touch alone. Target structures are relatively small and more deeply seated than in other organs, providing narrow working space to surgeons. Accordingly, early surgical risks were usually high. New surgical methods offered safer and more precise approaches via small or even blind fashion. In particular, introduction of image-guided neurosurgery (IGN) in the late 1970s made it possible to approach deep structures in the brain and, perform biopsies, injection, stimulation, implantation, or radiosurgery. In modern times, brain structures are virtualized in real time, leading to developments in brain tumor treatment and functional neurosurgery. Most stereotactic procedures are conducted with anatomical targeting based on brain atlases and neuroimaging, so technological advancements have great importance.

The aim of this study is to give an overview of current practices and pitfalls of IGN and suggest future directions.

Imaging Modalities for IGN

Initial development of IGN was rapid. Ventriculography and pneumoencephalography established anatomical references, such as the anterior-commissure (AC) and posterior-commissure (PC) line. These two landmarks supported the development of the main atlases of the human brain (1, 3, 4). Cerebral angiography showed the three-dimensional characteristics of the cerebral vasculature and its relationship with intracranial lesions, especially in tumor or vascular malformations. IGN underwent a second revolutionary change after computed tomography (CT) scans became available in clinics. CT provides direct visualization of intracranial structures and accurate stereotactic localization due to its reduced image distortions. CT has negative features such as low image resolution, susceptibility to metal artifacts, and a high x-ray radiation load to the patient. Magnetic resonance imaging (MRI) presented exquisite anatomical information in three directional axes (axial, sagittal, coronal). It had high image resolution, making it possible to visualize the vessels with gadolinium contrast. There were, however, shortcomings: image distortions, relatively long scan times, and potential hazards associated with implanted devices. In the modern era, multimodal imaging began to use fusion techniques based on contours, image intensity and voxel matching. These merged data allowed surgeons more available information about their patients. Furthermore, frameless stereotactic navigation systems are now available for minimally invasive real-time localization.

Current Practice of Stereotactic IGN

Deep brain stimulation (DBS)

Deep brain stimulation (DBS) is a well-known neuromodulation therapy for a wide range of clinical fields. It is used to treat movement disorders, such as Parkinson's disease (PD), essential tremor (ET), and dystonia, as well as refractory psychiatric disorders such as obsessive-compulsive disorder, depression, and Tourette syndrome. In the past, lesioning procedures were popular, but DBS became preferred because of its reversibility and adjustability. DBS provides electrical stimulation to specific functional targets by inserting electrodes into deep brain structures related to motor or limbic circuits.

In DBS, localization depends anatomical and physiological targeting. Anatomical localization uses the connecting line between the AC and PC as a reference. Three-dimensional coordinates (X, Y, Z) are used to target a point based on the brain atlas. Visible structures from CT or MRI scans are then combined to match the target (Fig. 1). Physiological localization also helps in identifying different basal ganglia and thalamic nuclei on the basis of electrophysiological properties. As physiological targets are generally not visible on neuroimages, the typical firing pattern of each target is used to recognize accurate placement of the electrode and predict side effects of electrical stimulation. In summary, whole DBS procedures are performed under the combination of atlas-based, image guided targeting and electrophysiological monitoring through microelectrode recording (MER).

PD is the main indication of DBS, especially in patients with dopamine-resistant symptoms, motor fluctuations, and levodopa-induced dyskinesia (5, 6). The subthalamic nucleus (STN) is a key structure in the basal ganglia-thalamo-cortical motor cir-

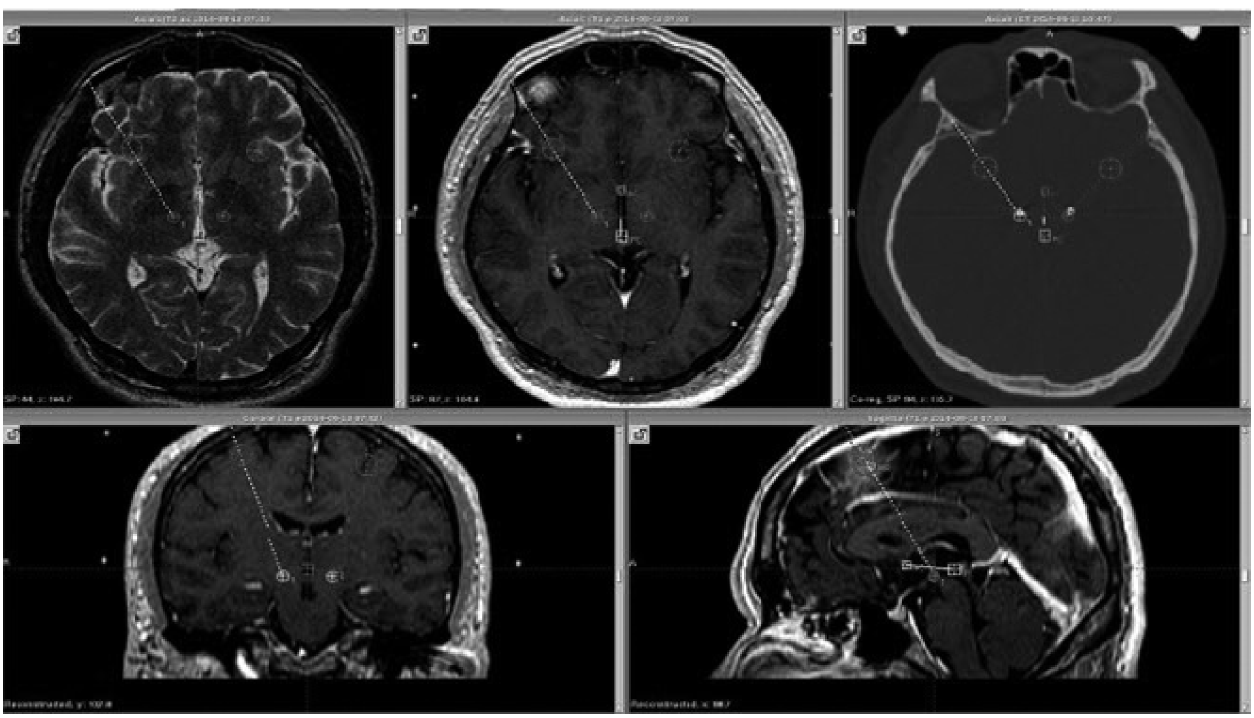

Fig. 1. Preoperative planning of deep brain stimulation in a patient with Parkinson disease (Leksell SurgiPlan®, Elekta AB, Sweden). Brain images of axial, coronal and sagittal magnetic resonance imaging and computed tomography show not only target points at the bilateral subthalamic nucleus but also the entry point and, insertion trajectory.

cuit, and DBS of the STN showed striking improvements, of 41–55%, in motor function (5, 7-10). The globus pallidus internus (GPi) is also an important stimulation target, demonstrating similar improvements in motor symptoms to STN DBS. GPi DBS has also been helpful in several types of dystonia, particularly primary dystonia related to DYT1 gene mutation (11, 12). In ET, patients suffer from severe tremor that impairs daily life. DBS of the ventrointermediate nucleus (Vim) of the thalamus showed remarkable reductions (75–90%) in tremor score, improving quality of life (13-16). In patients with psychiatric disorders, DBS can be targeted to white matter tracts in the anterior limb of the internal capsule (ALIC), ventral capsule (VC), and inferior thalamic peduncle (ITP), as well as to gray matter structures in the ventral striatum (VS), nucleus accumbens (NAc), and STN (5, 17, 18)

DBS requires a high degree of accuracy because a tiny error, even 2–3 mm, can cause critical problems in patients. IGN has improved neurosurgical outcomes through stereotactic techniques, yet, further study is necessary to overcome unsolved technical issues and ensure better outcomes.

Gamma knife radiosurgery (GKRS)

Radiosurgery developed by Lars Leksell as a non-invasive technique to destroy intracranial disorders with single, high-dose ionizing beams (19). Technical developments were thereafter achieved in the domain of radiosurgery devices and radiation sources, as well as surgical aspects such as irradiation technology and dose planning. In contrast to conventional radiotherapy, gamma knife radiosurgery (GKRS) precisely delivers highly fractionated radiation focusing multiple beams on a defined tar-

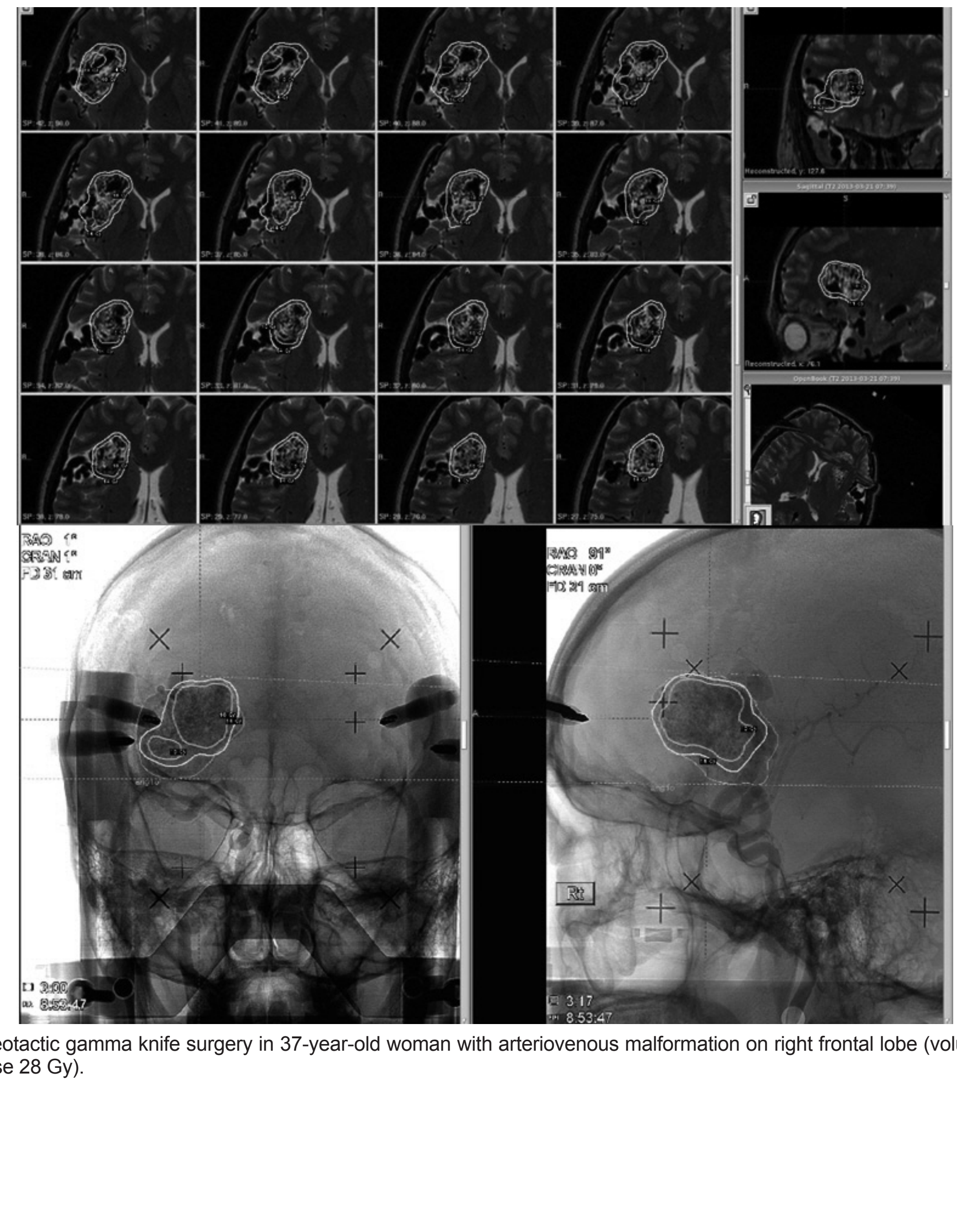

Fig. 2. Stereotactic gamma knife surgery in 37-year-old woman with arteriovenous malformation on right frontal lobe (volume 15.2 mL, maximal dose 28 Gy).

get volume under stereotactic conditions (Fig. 2). Normal tissue around the target receives minimal dose due to the small field size and sharp dose fall-off of radiosurgery (20). Radiation effects at cellular level are mostly direct DNA damage, and lesions produced by free radicals. Patients wear a frame on their heads while scanned by MRI, then target points are established in treatment planning software based on imaging modalities like MRI, CT, positron emission tomography (PET), and angiography. Patients can be treated in a minimally invasive fashion and return to usual activities the next day. GKRS has found applications as a primary strategy or adjuvant therapy in a number of clinical fields including intracranial tumors, vascular malformations, psychiatric disorders, and functional disorders such as pain, movement disorder, and epilepsy (21-25). Despite risks of radiation-induced adverse effects, GKRS is now an indispensable neurosurgical tool, especially in cases where the lesion is too hard to approach with standard neurosurgery and the patient's condition not good enough to endure open surgery (26).

GKRS must be precise to prevent serious adverse biological events. Advancement in neuroimaging and image-guidance techniques are thus essential to the safety and effectiveness of GKRS.

Stereoelectroencephalography (SEEG) implantation

Stereoelectroencephalography (SEEG) is a safe and accurate method of invasive recording used to identify the epileptogenic zone (EZ) in some patients with medically refractory epilepsy, particularly in surgical cases where noninvasive investigations like scalp electroencephalography and, imaging tools have failed (27). SEEG is a stereotactic technique for implantation of multilead electrodes in suspicious intracerebral structures based on a working hypothesis from analysis of noninvasive data. SEEG can be combined with thermocoagulation to lesion a targeted area for treatment (28). It permits precise recordings of deep-seated structures, bilateral explorations, or maps of ictal onset and propagation. In addition, it avoids large craniotomies compared with subdural electrodes. Stereotactic implantation is performed following the Talairach method (29). Preoperative planning should always consider the accurate targeting of the desired brain structures and avoid the risk of intracranial or cortical vessel injury. According to circumstances, it may require not only basic MRI images but also functional MRI, and diffusion tensor imaging to preserve functionally critical structures (30). Recently, SEEG has been updated with high-resolution neuroimaging and robotic stereotactic systems. Constant technological efforts are vital to decrease safety and accuracy issues.

Magnetic resonance-guided focused ultrasound (MRgFUS)

Magnetic resonance-guided focused ultrasound (MRgFUS) is a non-invasive lesioning procedure using focused ultrasound and frame- and image-based guidance. Thermal ablation can be performed when energy from high-intensity acoustic waves is absorbed by target tissues (31). It can also cause inertial cavitation (32). Because energy absorption in the ultrasound beam path is low, surrounding normal tissue is spared. MRgFUS enables ultrasonic energy to be focused through the intact skull, allowing application in psychosurgery and functional neurosurgery, such as thalamotomy for ET and, subthalamotomy for PD (33-35). Another potential approach in cases of central nervous system (CNS) tumor disrupts the blood-brain barrier (BBB) and delivers therapeutic agents directly into the brain. MRgFUS has a major benefit in its non-invasiveness, as well as less side effects compared with other lesioning modalities like radiofrequency procedure or GKRS. Additionally, accuracy can be monitored during procedures via real-time, closed-loop monitoring of MR thermometry and sequential MR images. Currently, temperature increase is the main factor associated with successful results, and, studies identify skull volume and skull density ratio as important factors affecting thermal rise during MRgFUS (36).

MRgFUS is one of the most outstanding surgical techniques. It is purely image-guided, not coordinate-guided surgery. Consequently, more accurate neuroimaging guidance is indispensable for targeting small, deeply located structures. Although low spatial resolution and signal-to-noise ratios (SNR) are limiting factors, continuous study of these issues is expected to contribute to broad application of MRgFUS. Clinical and experimental trials are proceeding on optimal indications and favorable outcomes of these new procedures.

Pitfalls and Trouble Shootings in IGN

Although stereotactic procedures attempt to be as accurate as possible in positioning the electrode at target points, positioning may actually be incorrect because of brain shifting, device error, surgical mistakes, or image related factors. Stereotactic neurosurgeons have attempted to overcome these problems. Particularly in invasive procedures, they concentrate on allowing as little cerebrospinal fluid (CSF) leakage as possible and pay special attention to diuretics use or hyperventilation (37). IGN is a blind practice, the most fearful complication of which is intracranial hemorrhage, reported as approximately 1.5–2.2% per lead and 2.6–4.3% per patient (38, 39). To prevent this, stereotactic surgeons use image-guided trajectory planning before electrode insertion, planning pathways to avoid blood ves-

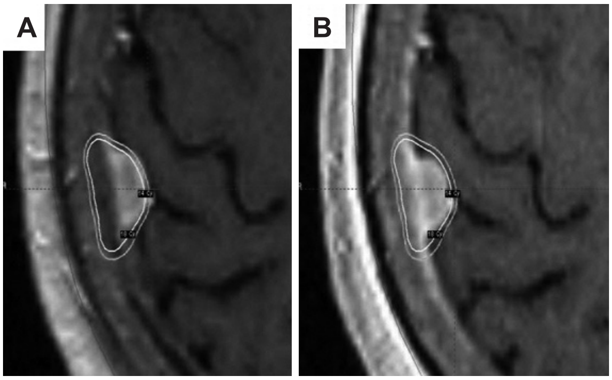

Fig. 3. Magnetic resonance image distortion due to differences in frequency encoding direction in gamma knife radiosurgery for a convexity meningioma. Left side image (A) obtained in a right to left direction shows different target delineation in the 50% isodose line compared with the right image (B), taken from an anterior to posterior direction.

sels, sulci, or ventricles visible in the MRI. Other physiological methods or functional neuroimages are frequently added to confirm optimal targets and decrease gaps between desired targets and actual locations. Other limitations are image related, such as resolution limits, mismatches of co-registration, image artifacts from metal or dental devices, and image shifting errors from frequency encoding directions (Fig. 3) (40, 41). These can cause serious mis-targeting during IGN, resulting in unfavorable outcomes, and lowering the reliability and accuracy of IGN. Even though image distortion produced by a 1.5 T MRI is less than 0.5 mm and acceptable for performing procedures, the current state of imaging accuracy should be improved (42). A recent study reported that errors associated with tracking, tool calibration and registration played a significant role in IGN and should be corrected for surgical accuracy (43).

Conclusion

IGN continues to develop in neurosurgical fields, moving toward non-invasive, more precise localization and increased safety and allowing access to functionally eloquent or surgically unavailable targets. IGN also has potential to expand into more treatments, including of existing conditions. The combination of conventional imaging and nanotechnology can be beneficial for defining the target area for pathology with high specificity. Additionally, as mentioned above, opening the BBB via focused ultrasound may introduce innovative approaches for treating CNS tumors. Image-guided gene delivery or stem cell homing are also potentially promising applications of IGN. In the near future, further progress in neuroimaging technology and software may contribute not only to more sophisticated and safer treatments but also better treatment outcomes for brain disease.

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