Techniques for Stereotactic Neurosurgery: Beyond the Frame, Toward the Intraoperative Magnetic Resonance Imaging—Guided and Robot-Assisted Approaches

Ziyan Guo[1], Martin Chun-Wing Leong[1], Hao Su[2], Ka-Wai Kwok[1], Danny Tat-Ming Chan[3], Wai-Sang Poon[3]

Key words
- Image-guided intervention
- Magnetic resonance imaging (MRI)
- Stereotactic neurosurgery

Abbreviations and Acronyms
3D: Three-dimensional
CT: Computed tomography
DBS: Deep brain stimulation
DoF: Degree of freedom
EM: Electromagnetic
LITT: Laser interstitial thermal therapy
MR: Magnetic resonance
MRI: Magnetic resonance imaging

From the [1]Department of Mechanical Engineering, The University of Hong Kong, Hong Kong; [2]Department of Mechanical Engineering, City University of New York, New York, USA; and [3]Division of Neurosurgery, Department of Surgery, Prince of Wales Hospital, The Chinese University of Hong Kong, Hong Kong

To whom correspondence should be addressed:
Ka-Wai Kwok, Ph.D.
[E-mail: kwokkw@hku.hk]

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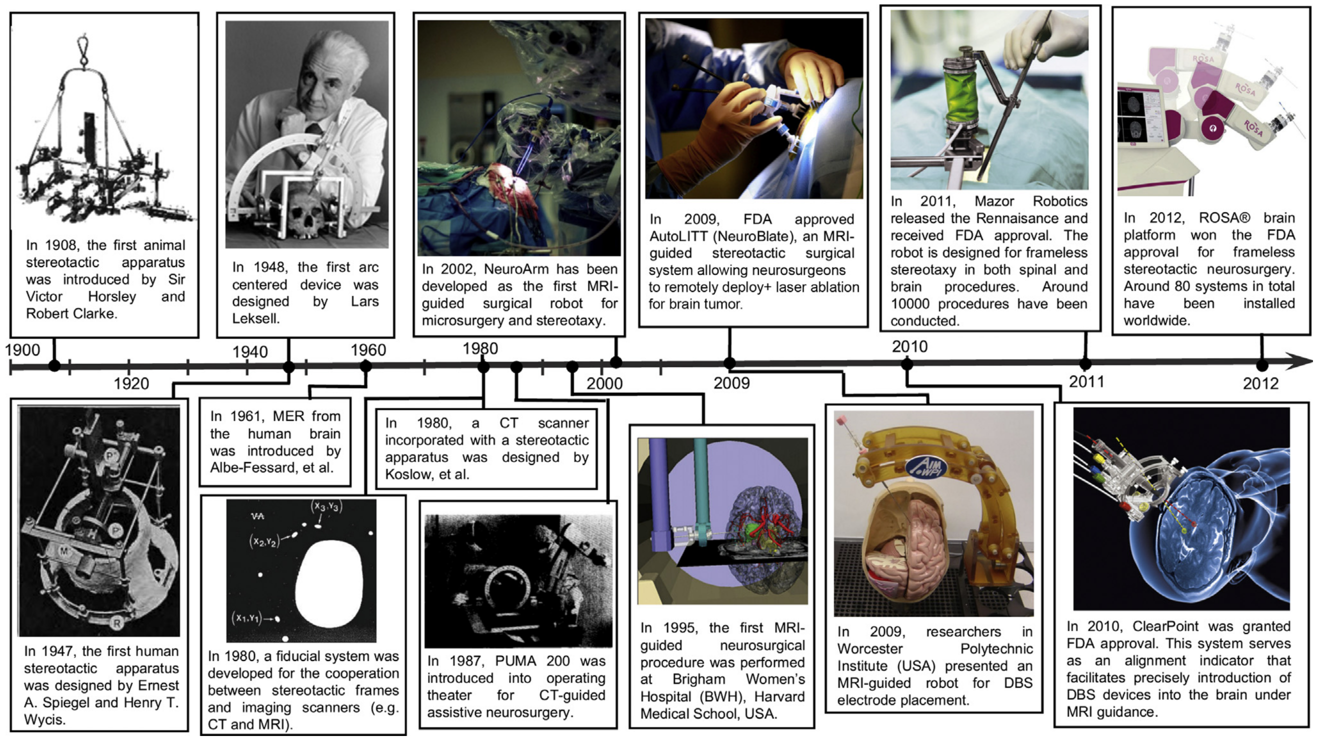
The development of stereotaxy can be dated back 100 years. However, most stereotactic neurosurgery still relies on the workflow established about half a century ago. With the arrival of computer-assisted navigation, numerous studies to improve the neurosurgical technique have been reported, leading to frameless and magnetic resonance imaging (MRI)-guided/verified techniques. Frameless stereotaxy has been proved to be comparable to frame-based stereotaxy in accuracy, diagnostic yield, morbidity, and mortality. The incorporation of intraoperative MRI guidance in frameless techniques is considered an appealing method that could simplify workflow by reducing coregistration errors in different imaging modalities, conducting general anesthesia, and monitoring the surgical progress. In light of this situation, manually operated platforms have emerged for MRI-guided frameless procedures. However, these procedures could still be complicated and time-consuming because of the intensive manual operation required. To further simplify the procedure and enhance accuracy, robotics was introduced. Robots have superior capabilities over humans in certain tasks, especially those that are limited by space, accuracy demanding, intensive, and tedious. Clinical benefits have been shown in the recent surge of robot-assisted surgical interventions. We review the state-of-the-art intraoperative MRI-guided robotic platforms for stereotactic neurosurgery. To improve the surgical workflow and achieve greater clinical penetration, 3 key enabling techniques are proposed with emphasis on their current status, limitations, and future trends.

BACKGROUND

Stereotactic neurosurgery is a technique that can locate targets of interest within the brain using a three-dimensional (3D) coordinate system.[1] Stereotactic approaches have been widely used in a variety of procedures, such as biopsy, injection, ablation, catheter placement, stereoelectroencephalography, and deep brain stimulation (DBS). The current workflow for stereotaxy comprises 3 primary stages: 1) preoperative planning, which requires imaging conducted before operation; computed tomography (CT) and/or magnetic resonance (MR) imaging (MRI) (e.g., gadolinium-enhanced volumetric MRI) are the 2 common imaging modalities that can offer precise lesion localization, in targeting of deep brain structures for treatment of functional disorders, MRI is advantageous in visualizing tissue such as deep brain nuclei in high tissue resolution and evaluating these structures with functional imaging techniques; 2) immediate planning with frame, which is a stage involving 3D coordinates registration between the images and the stereotactic frame; image fusion is commonly adopted in this step, in which CT images are usually fused with preoperative MRI for surgical planning; 3) intraoperative refinement, which includes setting up the platform for the coordinates and trajectory; a burr hole and dural puncture are made. Conventional stereotaxy for DBS includes microelectrode recording and macrostimulation for physiologic validation.

Despite the standard workflow that has been established for decades, stereotactic surgery still remains challenging, particularly because of the high demand for precision and minimal invasiveness. Imprecise positioning of instruments results in a deviated trajectory and targeting error, which significantly increases the risk of hemorrhage. In the current workflow, several strategies are used to limit the error.[2,3] Patients are positioned in a similar way to the scanning position. During surgery, brain shift can be reduced in several ways. Minimal cerebrospinal fluid can be achieved by 1) placing the 14-mm burr hole and a small dural opening (3—4 mm) on a gyrus rather than a sulcus, 2) flooding the burr hole with saline irrigation after dural opening, and 3) sealing the dural defect with fibrin glue as soon as the electrode is in situ and before test stimulation. However, these strategies still cannot compensate for the changing conditions during surgery without continuous updates of instrument position relative to the target. Registration (image fusion) at the planning stage may provide only a 1-time calibration for the surgical roadmap based on the preoperative images. Errors



In 1908, the first animal stereotactic apparatus was introduced by Sir Victor Horsley and Robert Clarke.

In 1948, the first arc centered device was designed by Lars Leksell.

In 2002, NeuroArm has been developed as the first MRI-guided surgical robot for microsurgery and stereotaxy.

In 2009, FDA approved AutoLITT (NeuroBlate), an MRI-guided stereotactic surgical system allowing neurosurgeons to remotely deploy+ laser ablation for brain tumor.

In 2011, Mazor Robotics released the Rennaisance and received FDA approval. The robot is designed for frameless stereotaxy in both spinal and brain procedures. Around 10000 procedures have been conducted.

In 2012, ROSA® brain platform won the FDA approval for frameless stereotactic neurosurgery. Around 80 systems in total have been installed worldwide.

In 1947, the first human stereotactic apparatus was designed by Ernest A. Spiegel and Henry T. Wycis.

In 1961, MER from the human brain was introduced by Albe-Fessard, et al.

In 1980, a fiducial system was developed for the cooperation between stereotactic frames and imaging scanners (e.g. CT and MRI).

In 1980, a CT scanner incorporated with a stereotactic apparatus was designed by Koslow, et al.

In 1987, PUMA 200 was introduced into operating theater for CT-guided assistive neurosurgery.

In 1995, the first MRI-guided neurosurgical procedure was performed at Brigham Women's Hospital (BWH), Harvard Medical School, USA.

In 2009, researchers in Worcester Polytechnic Institute (USA) presented an MRI-guided robot for DBS electrode placement.

In 2010, ClearPoint was granted FDA approval. This system serves as an alignment indicator that facilitates precisely introduction of DBS devices into the brain under MRI guidance.

Figure 1. Milestones of image-guided devices for stereotactic neurosurgery. CT, computed tomography; DBS, deep brain stimulation; FDA, U.S. Food and Drug Administration; MER, microelectrode recording; MRI, magnetic resonance imaging.

can still come from various sources: 1) lead time between scanning and surgery; 2) mechanical error of the frame; 3) number of sampling fiducial points for registration; and 4) intrinsic error in image fusion. Once the dura is opened, brain shift/deformation inevitably causes changes of both critical brain structures and target positions. During surgery, brain deformation occurs in response to many factors of surgical manipulation and anesthesia procedures such as intracranial pressure changes, postural and gravitational forces, tissue removal, administration of pharmaceuticals, and edema caused by surgery. Therefore, using only preoperative images to form the roadmap seems to be the major disadvantage in the current workflow for stereotaxy.

In the context of current neurosurgical challenges, the incorporation of advances in real-time visualization and precise manipulation is imminent for brain shift compensation and workflow simplification. MRI possesses several advantages over other imaging modalities (e.g., ultrasonography or CT) for intraoperative guidance, because of its high sensitivity to intracranial pathologic/physiologic changes and ability to visualize soft tissue in high-contrast images without ionizing radiation. Fast MRI sequences (such as radial fast imaging using low angle shot sequence with a temporal resolution of 20—30 milliseconds[4]) have been widely available in MRI facilities and have already enabled surgical guidance when involving soft tissue deformation. The field is ready for an MRI-guided robot to find its way into more complex procedures, which would provide precise stereotactic guidance to deliver image-guided therapy, such as device implantation or tissue ablation. In this review, we provide a discussion regarding the state-of-the-art apparatus and MRI-safe/conditional robots for stereotactic neurosurgery, as well as the key enabling techniques with emphasis on their status, limitations, and future trends.

NEEDS FOR CURRENT APPARATUS AND MRI-GUIDED ROBOTIC SYSTEMS

The introduction of computer-based image navigation systems has allowed intraoperative guidance based on preoperative images since the 1990s (the evolution of devices in stereotactic neurosurgery is shown in Figure 1).[5] These advances in both imaging and tracking technologies enable frameless stereotaxy to be increasingly used. Frameless techniques use landmarks (e.g., facial contours) or fiducial markers to replace the frame for registration between images and operation space. Particularly, its incorporation with intraoperative MRI guidance can optimize the procedure by providing real-time positional information of imaged brain/surgical instruments, compensating brain shift, reducing registration errors, monitoring surgical progress, and performing MRI-based verification instead of physiologic assessment for DBS.[6,7]

Several clinical trials have been conducted using manually operated MR-safe/conditional stereotactic platforms (e.g., NexFrame [Medtronic Inc., Minneapolis, Minnesota, USA] and SmartFrame [ClearPoint, MRI Interventions Inc., Irvine, California, USA].[3,8-10] The ClearPoint system (Figure 2A) has been deployed in several therapeutic approaches (e.g.,