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STEREOTACTIC NEUROSURGERY ROBOT: AN OVERVIEW

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ABSTRACT

The brain is a sensitive and complex organ in the human body that must be handled with great care. Brain morbidities are unavoidable. This article examined the historical context and provided an insight literature overview on stereotactic neurosurgery robots. The existing neurosurgical robot that has FDA clearance have exorbitant cost. A handful of robots are promising but yet to be in clinical use, which, if brought to the healthcare system, may provide utmost care and reduce neurosurgical mortality. It was found from the study that, close chain robots are almost unwelcome in neurosurgery application. This limiting factor may be attributed to the workspace and dexterity, which may not be applicable to some surgeries. There is an unnecessary Dof in some robotic systems which added structural and control complexity. The review also witness the superiority performance of some of the robots over the others though they belongs to the same class.

Keywords: Stereotaxis; medical robot; deep brain stimulation (DBS); intracerebral hemorrhage (ICH); thermal ablation; hydrocephalus; minimally invasive

1. INTRODUCTION

Stereotaxis in neurosurgery represented a significant advancement by providing the least invasive surgery to the brain. Pioneering work by Spiegel and Wycis developed the first commonly used stereotactic system in 1947 for the human brain (Kwoh et al., 1988). It serves as a constant reference between external markers on the skull and lesions occupied areas inside the brain. New stereotactic frame designs, which incorporated Cartesian targeting, angular trajectory, and advanced imaging techniques like computed tomography (CT) and magnetic resonance imaging (MRI), made it possible to reach subcortical regions of the brain with higher precision. It received a broader use in tumor resection, deep brain stimulation (DBS), encephalitis, Gerstmann's syndrome, hydrocephalus, intracerebral hemorrhage (ICH), radiation delivery, epilepsy therapy, and variety of other treatments (Rahman et al., 2009). Usually, stereotactic neurosurgery depended on a coordinate system embedded with the frame and a technique to link those coordinates with the patient and their imaging. Although conventional frame-based methods are still precise and dependable, they have a number of disadvantages.

The primary disadvantage is that the patient must remain tightly fastened in the frame throughout the surgery in order to preserve this connection, not intuitive, complicated steps, head immobilization, patient discomfort, and less accuracy in tool placement (Li et al., 2014). Furthermore, no intraoperative real-time image that provides the surgeon with extra information on the entrance angle, tool position, 3D localization picture of the target, and feedback force and torque sensor used on the brain (Hartkens et al., 2003). The surgeon has no visual connection to the operation site, just left with his experience. Alteration for another path to the target turns to be irksome and time-absorbing.

This resulted in the development of several robots and manipulation devices in the field of neurosurgery. The advancement of science and technology also affects the transition from traditional stereotaxis equipment to the use of highly intelligent stereotactic surgical robots in the operating theater, which vastly reform the procedure and decrease surgery trauma. The aims of the paper is to give a broader review on the neurosurgery robots for MRI-unconditional which might save the readers time searching many articles and help healthcare givers in search of an appropriate tools for neurosurgery. Moreover, the paper also intended to provide a leeway for those wish to bring the abandon project into existence.

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2. SURGICAL PROCEDURE INSIGHT

There are many established neurosurgical procedures for the treatment of brain diseases that does not require large opening. Each established procedure goes with specific functionality, but the general approach is highlighted below.

Preoperative planning: In this stage, an MRI image or any functional medical scan of the high resolution of the area suspected with a problem is obtained (Starr et al., 2014). The MRI image series usually comprises a high-resolution coronal T2 sequence, a high-resolution magnetization prepared axial T1 sequence, and a post gadolinium magnetization prepared axial T1 sequence transformed into three 3-D using appropriate modality to obtain precise information. Equally, a volumetric CT angiogram of the suspected area with its bony volume is conducted with or without frame at the day of surgery. The obtained 3-D images give a distinct anatomical peculiarity of the target area for navigation.

Surgical Planning: At this stage, the clinician uses the information from the preoperative stage to define the target (surface contour, area, volume) and other anatomical features surrounding the target (Karas and Chiocca, 2007). Target definition can be automatic or manual, and it depends on the software and the surgeon interest, different modality exists for defining the target. The surgeon proceeds to come up with the entry point and best (optimal) path for reaching the target by avoiding healthy tissues.

Intraoperative Registration and Navigation: There is no unique intraoperative registration. Different systems adapt to different registration. In a nutshell, patient images from preoperative space are used (both the CT and MRI). The images coordinates are extrapolated based on a fiducial marker or stereotactic reference frame within the robot reference coordinates system (i.e., computation of the transformation among the image space, with reference to the anterior-posterior commissure line, and the fiducial marker or stereotaxis reference frame) (Drake et al., 1991, Guo et al., 2018b, Giorgi and Marcenaro, 1982). A validation simulation is performed to see whether the system is correctly matched with the patient coordinate system or not. After validation, skin laceration, bone drilling, and dura matter perforation are executed out by a robot under imaging machines, and then other surgical tools are manipulated towards the target (Lehocky et al., 2014). The necessary update is also provided at this stage for greater accuracy. Fig. 1 depicts a comparison summary between the traditional stereotactic neurosurgery and CT/MRI-guided robot-assisted stereotactic neurosurgery. The figure highlighted the error sources in both the methods and the steps undergo before and after the surgery. Few steps with visuality of operation site means less error.

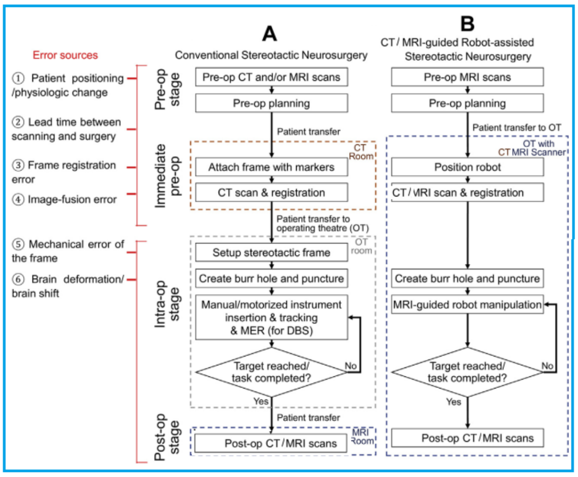

Fig. 1. Surgical workflows for traditional stereotactic neurosurgery (A) and CT/MRI guided robot-assisted stereotactic neurosurgery (B)(Guo et al., 2018a).

2.1. Goal of Robot in Stereotactic Neurosurgery and its Functions

The ultimate goal of using a robot is to provide the best possible treatment for the patients. Throughout a neurosurgical operation, the robot performs a variety of functions. Some researchers (Kwoh et al., 1988, Lirov and Vannier 1986, Raoufi et al., 2008, Zamorano et al., 2004) reported that because of the robot arm's steady movement, unlike human hands, it achieves high positioning and orientation accuracy, precision in handling surgical tools to reach the target, and adapt/react/adapt to the environment like humans.

Robots are able to apply force to an organ with greater precision and delicacy than humans. Scale-up/down force and motion in a remotely operated robot; accomplish precise trajectory motions that avoid nearby healthy tissues. It can carry hefty surgical instruments that are nearly hard to grasp with a human hand, and it can also administer radioactive medicines that might harm people. The entire operation may be optimized because of its ability to communicate with monitoring systems and other equipment. The neurosurgical robot's most notable feature is frameless surgery. Nonetheless, reliability is an area where more can be done.

2.1. Categorization of Surgical Robots

Many surgical robots exist, but the Tailor's categorization was usually regarded as the most renowned. Surgical robots are categorized based on the following criteria (Nathoo et al., 2005).

- Tele-surgical systems
- precise positioning systems
- Precise path systems
- Navigational aids

Moreover, medical robots are classed as passive, active (autonomous), or semi-autonomous, depending on their technical design. In passive mechanisms, the surgeon manually drives the system with his or her energy, but in autonomous robots, the doctor observes the entire operation and intervenes when something goes wrong. This necessitates the employment of computer systems with intricate algorithms (Fomenko and Serletis 2018). Semi-autonomous robots are best described as synergetic devices in which the robot and the clinician engage to a greater extent.

3. STATES OF THE ART

This part briefly reviews the robotic neurosurgical systems incompatible with MRI scanners solely designed to be used with CT or C-Fluoroscopy based on classification (operational control architecture) not base on their applications, although some are dedicated to a particular operation like a biopsy, microsurgery, laser ablation, aspiration, electrode implantations e.t.c. The main features of each system are compiled in table 1. Likewise, Fig. 2. depicted the robots images based on year of debut.

Table 1: Summary of MR non-stealth robotic systems

System	Institution	Country	Year	Applied to	Regulatory status	Mount	DOF	RCM	Back drivability	Ref
A. SUPERVISORY CONTROLLED										
IGOR	Grenoble Univ.	France	1991	Human	Non-commercial	Floor	6	-	Very low	(Lavallee 1989, Lavallee et al., 1992)
Minerva	Lausanne Univ.	Switz.	1992	Human	Non-commercial	Scanner floor	6	-	Low	(Villotte et al., 1992)
Neuro-Mate	Renishaw	France/ USA	1997	Human	Commercial	Floor trolley	5	-	Very low	(Diodato et al., 2004)
Pathfinder	Prosurgics/ Univ. of Nottingham	UK	2003	Phantom	Non-commercial	Mobile base	6	-	Very low	(Morgan et al., 2003)
Renaissance	Mazor Robotics Ltd., Caesarea,	Israel	2005	Human	Commercial	Skull	6	-	Very low	(Joskowicz et al., 2005)
Niss Robot	Nat. Neuroscience Inst., Singapore	Sing.	2009	Animal	_	Mobile base	7	_	Very low	(Chan et al., 2009)
SurgiScope	(ISIS Intel. Surgical Instr. & Sys., Grenoble)	France	1989	Human	Commercial	Ceiling	7	-	Low	Briot et al., 2007,
B. TELE-SURGICAL AND SUPERVISORY CONTROLLED										
Robocast	-	Italy	2007	Phantom	Non-commercial	Mobile base	13	-	Low	(De Momi et al., 2010)

TOMS System	Chonnam Univ. Gwangju	Korea	2009	-	Non-commercial	Scanner floor	4	-	Low	(Seung et al., 2009)
C. SUPERVISORY CONTROLLED AND SHARED CONTROL										
Rosa	Medtech Surg., Inc, Montpellier France	France	2012	Human	Commercial	Mobile base	6	-	Low	(Lefranc et al., 2014)

3.1. Supervisory Controlled

IGOR project was conceived at Grenoble University France, which has 6-DOF and used pre-operation planning workstation imaging and tracking system that process digital images from x-ray and CT scanners, allowing the surgeon to change marking during the procedure (Lavallee 1989, Lavallee et al., 1992). From 1989 to 1992, the robot performed over 400 interventions for brain-related problems. IGOR project never enjoys commercial use.

Minerva was also among the earliest neurosurgery robot originated from Switzerland Lausanne University. The robot consists of four prismatic joints (1-2-5-6) for positioning and insertion and two revolute joints (3-4) for orientation. It utilizes a pre-operation planning workstation imaging integrated with a CT scanner, giving the surgeon a view of the surgical site in due course. Joints 1-4 are lock and disengaged from the control scheme once the target entry point and desired path are achieved (irreversible). Sequentially, joint 5 advances link 5 to the head until the rotating surgical knife attached to the arm end touches the skull and locks and disengages from the control system. Only prismatic axis 6 (reversible) is under control and allowed to move the biopsy needle for traction and retraction (Villotte et al., 1992).

Since its provenance, the robot conducted biopsies and cyst evacuations procedures(Diodato et al., 2004). One outstanding feature of Minerva is its ability to carry many surgical tools at a time, with a drawback of safety due to the limitation of single-dimensional incursions that halt the project later.

NeuroMate is a prominent 5-DoF neurosurgery robot fixed to the floor. It is originated from France/USA. The robot was developed by Renishaw with an accuracy of 0.7 mm, a precision of 0.15 mm, and a payload capacity up to 5kg, intended to be used with a frame or without a frame. Some researchers in (Cardinale et al., 2013) points out that the robot gets in vivo localization error of 0.86 ± 0.54mm at the entry point and 2.04 ± 1.31mm at the target point using a frame-based approach (Faria et al., 2015). Researchers in (Li et al., 2002) deduced from the experiment that there is no significant disparity between the frame-based approach using NeuroMate and the traditional stereotactic frame. It comprises of pre-surgical planning workstation integrated with an imaging scanner. It can plot the feasible path to attain the target and plot a contour using preoperative information on the patient's skull.

After the entry target was located, the robot position, orient, and manipulate the surgical apparatus within the burr hole. It also can interact with the surgeon and accept the changes. Neuromate has conducted countless procedures worldwide since its conception, including biopsies, basal ganglia intervention, and electroencephalographic investigation of patients with epilepsy (Diodato et al., 2004). NeuroMate has a noble feature of low speed and excellent safety, this notable it from industrial manipulators(Faria et al., 2015). Considerable disadvantages of NeuroMate are its inability to drill a burr hole, hold a few surgical stuffs simultaneously, and its bulkiness. The Neuromate project is still in commercial use.

Pathfinder was produced by Prosurgics, formerly Armstrong Healthcare (UK). It is a robotic system of hardware and pre-surgical planning workstation integrated with an imaging scanner. The robot has 6-DoF revolute joints and is mounted on a mobile base for easy movement within the theater room or fix on Mayfield, with a micro head CCD camera on the end-effector to continuously locate the fiducial markers on the patient's head (frameless registration) to register the manipulator to the intraoperative area(Faria et al., 2015). The markers are of black titanium sphere put on a yellow disc that is simple to observe by the micro head CCD camera and CT scans. It utilizes the pre-operation planning imaging from CT scan and MRI to define the marker location in respect to the surgical place, segment the brain structures target, and an entry point. When integrated with a CT scanner, it allows the surgeon to change marking during the intervention. The robot has a repeatability of 0.4 mm and an overall application error of 2.7mm(Morgan et al., 2003).

Noteworthy features of the robot are its safety architecture (foot pedal to start or stop the robot movement, secondary encoders for further verification) and its ability to continuously trail its position in relation to the patient using an external fiducial marker. However, noted problems with the Pathfinder robot are undesirable skin shifts between preoperative and intraoperative scans and registration wreck created by the incorrect identification of markers due to unusual lighting circumstances(Morgan et al., 2003). Later on, Pathfinder's work was stopped.

Renaissance was developed in Israel by Mazor Robotics, has spinal and brain surgery capabilities. It acts as tool guidance, but the surgeon has to drill by himself. The frameless and markerless robot consists of a MARS (6-DoF miniature (5×8×8cm) parallel robot of weight 250g), robot base mounted on the skull or Mayfield, targeting device that provides tool guidance (for biopsy, MIS, electrode placement, and many more procedures), and a workstation that runs a planning software for acquiring the images, registration, calculation of kinematic parameters and real-time control(Shoham et al., 2007). It gets a 3D imaging advantage during the registration, in which the preoperative CT scan is matched with intraoperative fluoroscopic images and aligns them with the clamping device coordinate system. Before the image registration, a C-arm calibration is performed with a phantom of radio-opaque spheres of a known pattern to avoid fluoroscopic images distortion. During the intervention, the robot is locked after aligning the tool guide with a pre-defined entry point, subject to change on clinician request and withstand actuation forces of 1kg and lateral forces of 10kg(Shoham et al., 2007).
A study carried out by Joskowicz *et al.,*(Joskowicz et al., 2005) on phantom shows a target registration error of 0.65mm. Renaissance project was promoted in the US, South America, and Europe. The robot solved the head restraint demand problems in stereotactic frames, tracking needs by navigation devices and bulkiness associated with other robots. The major disadvantage of the Renaissance is limited working space.

Niss robot originated from advanced integrated medical systems and the National Neuroscience Institute, Singapore, intended for frameless registration use. The robot comprises four separate components: a NeuroPod, 5-Dof hexapod manipulator equipped with a force-torque sensor that carries surgical equipment and auxiliary instruments (surgical drill, a pointer) and conducts surgery. A NeuroBase, which is attached to the parallel manipulator that helps in positioning the hexapod robot in the best task workspace in relation to the patient and lock, a NeuroVision (Certus, Northern digital), an optical navigation system used as an intraoperative tracking system for both the manipulator and the patient, and a NeuroPlan, which is a workstation for planning and executing the surgery, it enables the physician to specify goals, paths, and critical locations to avoid(Chan et al., 2009). Three of the five hexapod joints are manually adjusted while motors power the remaining. The basic robot's present size is appropriate for use in an operating room. It has a 350 x 600 mm base size and an alterable height of 1180-1630 mm. The robot is mounted on the mobile base for easy movement and can build the needed trajectory automatically employing a proprietary path-generation algorithm. Prior to the commands are dispatched to the NeuroBase, the clinician double-checks the path. According to the preplanned workflow, the whole intervention procedure is carried out with the clinician monitoring, having a real and virtual view at the same time. An in vivo experiment with the robot indicated the needle tip deviated from the desired point on an average of 0.9 ± 0.6 mm when target locations were chosen from preoperative CT scans for computation; when target locations were chosen using postoperative CT scans, the deviation increase to an average of 1.5 ± 0.7 mm(Chan et al., 2009). There is no clear evidence about the project's commercialization.

SurgiScope was developed in France by ISIS Robotics, Saint Martin dH'eres. Like IGOR its development started at Grenoble University. It is a Delta parallel robot family mounted on the ceiling in which the robot's absolute position is changed by sliding its base on the ceiling rail. With the robot having 7-DoF modular architecture (Deblaise 2005), the user can choose the modules to work with(Faria et al., 2015). SurgiScope is used for a microscope-assisted neurosurgical intervention. It comprises a pre-surgical planning workstation integrated with an imaging scanner (Briot et al., 2007), a surgical tools holder kit such as a biopsy needle, and an endoscope. The record shows that the SurgiScope was the first robot to put forward frameless fiducial-based targeting together with preoperative MRI registration(Fomenko and Serletis 2018). The robot has a positioning error of 1.6±3.0mm from the end effector to the goal(Bekelis et al., 2012). SurgiScope project is not promoted and sold anymore. The robot's noteworthy features are multiple functional tools attachment holder and can be used as a microscope with path pave, with a disadvantage of lacking portability.

3.1. Tele-Surgical And Supervisory Controlled

Robocast system is a multi-robot architecture consisted of three robotic systems, with Pathfinder (discussed in 3.1.) used for approach, 6-DOF parallel manipulator used (MARS, Mazor discussed in 3.1.) as positioning device and correcting the surgical tools to the target and 1-DOF piezoelectric linear actuators produced by NearLab, Politecnico di Milano, Milan, Italy for insertion. It is made up of 13-DOF, with an accuracy of 0.15 as reported by the Certus optical system (NDI, Ontario, Canada) (De Momi et al., 2010). In the *Robocast* system, an Omega shape haptic device (Force Dimension, CH) is manipulated by the surgeon to advance the surgical tool. The force exerted by the brain as a result of the probe advancement is measured by estimating the controller input velocity signal. One noteworthy feature of Robocast is its ability to automatically plan the probe's trajectory with minimal risk of healthy brains tissue damage, subject to the physician's approval.
For a linear motion, in an *in-vitro* optical and induce noise condition, M. Comparetti *et al.,* (Comparetti et al., 2012) report a median error for entry and target point to be 0.6 and

0.4mm respectively and rotation error of 0.0065 rad, respectively. Later on, the Robocast project was terminated.
TOMS system originated from Chonnam University Gwangju, Korea. The manipulator is a teleoperation surgical system offered for MIS. The system is divided into three subsystems: master, slave, and remote control system. The technology allows for dual control, i.e., master-slave control and remote control via the internet's TCP/IP protocol. The master system is a manipulator of 4-Dof with one linear axis and three revolute axes designed as a hybrid having parallel and serial structure powered by MAXON DC motors with EPOS position controller. It is driven by a cable (except at roll axis) to command/drive the slave system, which is also built as 4-Dof (linear, yaw, pitch, and roll) and incorporates force feedback to control a component that moves an end-effector. To carry out the MIS effectively the slave robot's end-effector was designed to be small. TCP/IP communication is employed to transfer data from master to slave systems. Both the master and slave robots are controlled from a PC， with a teleoperation matching used to control the slave manipulator from the master robot rather than controlling the slave directly. Hence, all control data of the master system joints is transferred to the slave robot via the TCP/IP based remote control system. One noteworthy feature of the robot is that the system interacts with the master system via a wired or wireless network(Seung et al., 2009).

3.2. Supervisory Controlled And Shared Control

Rosa (Medtech Surgical, Inc, Montpellier France) is consists of a 6-DoF revolute joint robot mounted on a mobile base and pre-surgical planning workstation integrated with an imaging scanner. It has the capability of plotting the feasible path to access the target. It flexibility give it an advantage of performing an array of neurosurgical intervention worldwide with or without a frame. After the robot end-effector reached the entry point and locks itself, skin incision and skull drilling are carried out with cordless power drills. Since it possessed supervisory and shared control features, the clinician might operate at the module he/she decides. Rosa is among the first medical systems to treat refractory epilepsy by deploying laser ablation probes to epileptogenic periventricular heterotopic lesion(Fomenko and Serletis 2018). Many procedures were also conducted, like biopsies, DBS, ICH with the robot.

Some researchers like M. Lefranc *et al.,*(Lefranc et al., 2014) compared the robot registration with phantom and, in reality, using different image modalities and point out that the robot achieved an accuracy of 1.22mm for a frameless registration with CT and reference imaging. The outstanding device feature is its more than one registration option, operation reduction time, portability, and neuronavigation system. The project is still in commercial use with an exorbitant cost.

3.3. Challenges

The challenges facing neurosurgery robots are material compatibility and safey. Also, a larger number of the robotic systems still utilizes frame base registration. This brought many errors in the procedures. Lack of full automation and automation increase risk effect the robots greatly.

3.4. Feature Direction

Through the use of FDA-approved surgical robots in neurosurgery intervention, the quality of healthcare was change drastically most notably is in the field of DBS, thermal ablation, biopsy and keyhole surgery and others. Neurosurgical robots continues to develop and improve, emphasis must be paid to maneuverability and safety (at the electromechanical, hardware, software, and execution levels), high degree of precision and accuracy at entrance and target locations.
Mechatronics components design, quantitative patient state descriptions, and intuitively incorporating human input are further technological in medical robots that need extensive research. A ccount for errors caused by a wide range of factors such as noise in the signals generated by the machine or sensor interference have to be considered when designing a medical robot for greater accuracy. N eurosurgical software with a flexible user interface based on standard prerequisites for those procedures must be developed with a focus on unifying the entire platform wherever possible.

3.5. Summary

An overview to the developing robotic systems for MRI-incompatible stereotactic neurosurgery has been presented in this paper. Dexterity and precision are increased beyond manual operation using the robotic systems. Despite this, just a few of them have been extensively embraced. This may be due to the high cost of the usage and extra labor, among other factors. The devices enhances the surgical procedures and bring an efficacy to the healthcare.

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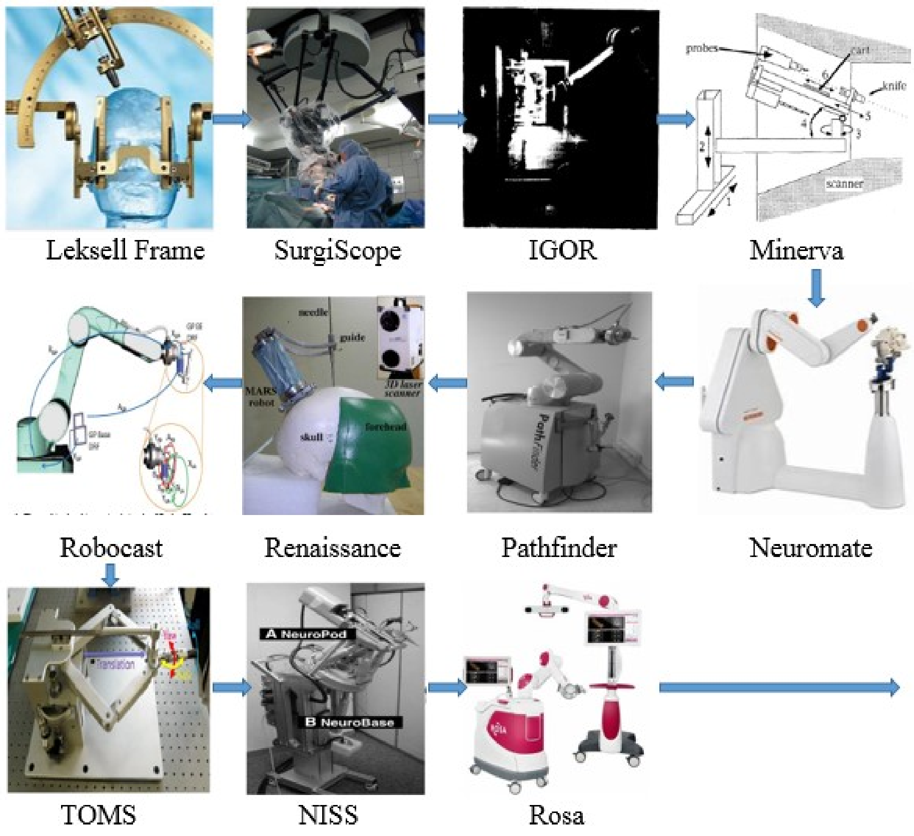

Fig. 2. Non-stealth robotic-assisted stereotactic neurosurgery based on the sequence of debut

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