28 Robotics in Cranial Neurosurgery

Benjamin I. Rapoport, Isabella Morgan, Turner Baker, Alexis Bruhat, and M. Sean Grady

Technological advances over the past two decades have contributed to the increasing role of robotics in a variety of industries, and several robotic systems have emerged as highly developed, integrated surgical tools in surgical subspecialties including urology, gynecology, head and neck surgery, colorectal surgery, cardiac surgery, and thoracic surgery. The robots currently used in these fields represent mature and highly dynamic assistive, though not yet autonomous systems. They combine advanced visualization techniques with minimal-access capabilities and versatile, multi-armed systems equipped with various tools, degrees of freedom not available to human hands, motion scaling and tremor correction, and some rudimentary forms of artificial intelligence. The robotic systems currently available for use in neurosurgery are more primitive and more limited in their utility. In both spinal and cranial neurosurgical applications, surgical robots are predominantly limited to static, stereotactic functions, guiding the surgeon to a trajectory but stopping short of assisting the neurosurgeon in a dynamic, cooperative manner. In this chapter, we begin by discussing several dominant robotic systems and technologies in current surgical use and other systems in advanced stages of research and development. We then review core principles of robotics as applicable to surgery. Finally, we address important factors limiting the progress of robotics in cranial neurosurgery. The era of robotic surgery has arrived, and future editions will undoubtedly see progressive development in this area.

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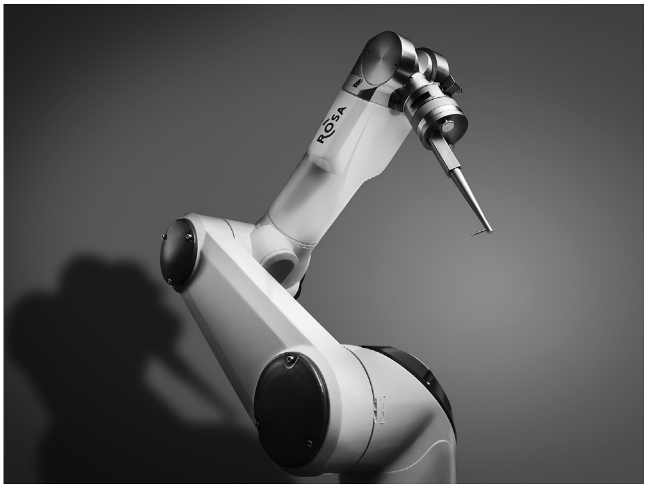

The ROSA ONE. The ROSA ONE robotic arm developed by Zimmer Biomet Robotics *(Courtesy LucileBssg/CC BY-SA 4.0. https://en.wikipedia.org/wiki/File:ROSA_One%C2%AE_Robot_.jpg.)*

The Da Vinci Robot. The Da Vinci surgical robotic system enables surgeons seated at consoles separate from the main sterile field to control a multi-arm robot performing a multiport surgery. At least one robotic arm typically holds a camera providing a view of the operative field (as shown on the screen in the image). An assistant remains sterile and is able to exchange instruments and physically manipulate the robotic arms as needed. *(Courtesy Intuitive Surgical, Sunnyvale, CA.)*

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KEY CONCEPTS

- A robot is a machine that is capable of autonomously executing sets of programmed actions.
- Most robots in commercial use comprise interacting mechanical and electrical systems, often integrating feedback from one or more sensors, under the control of a computer that is programmed to guide the entire system through specific tasks.
- Robots provide the ability to execute diverse sets of programmed instructions reliably and repeatedly, often with superhuman speed and accuracy. A ubiquitous feature of industrial robots is the articulated robotic arm, a design feature that dominates contemporary robotic surgery, in part because many such systems are intended to function like the arms and hands of a surgeon.
- Robotic systems in neurosurgery have been used extensively for stereotactic procedures, including electrode placement and biopsy, and to an increasing extent for minimally invasive ablation. Dexterous robots, with end effectors capable of implementing microsurgical manipulations, are not widely available in neurosurgery, though macrosurgical dexterous robots are in widespread use in other surgical specialties.
- Excellent haptic feedback, small instruments capable of microsurgical soft tissue management, high-precision image guidance and instrument tracking, and tools for bone removal are all required for progress in neurosurgical robotics. These advances are imminent.
- Contemporary machine learning techniques will likely lead to increasing levels of autonomy in surgical and neurosurgical robotic systems.

ROBOTS DEFINED

What is a robot? In contemporary use, the term *robot* refers to a machine, particularly one with human-like qualities, that is capable of autonomously executing sets of programmed actions. Most robots in commercial use comprise integrated mechanical and electrical systems, often with one or more sensors, under the control of a computer that is programmed to guide the entire system through specific tasks. In many industries, from automobile manufacture to electronics to health care and pharmaceuticals, robotic systems have become essential to the reliable production of high-quality goods and services, providing the ability to execute diverse sets of programmed instructions reliably and repeatedly, often with superhuman speed and accuracy. A ubiquitous feature of industrial robots is the articulated robotic arm. This type of robot has emerged as a dominant design in contemporary robotic surgery, which is perhaps not surprising given that these robots are in many cases intended to function like the arms and hands of a surgeon.

In the next section, we provide a survey of robotic systems currently used in neurosurgery. This survey provides context for the following sections. We subsequently discuss several important principles of modern robotics as they apply to neurosurgical robotics, with an emphasis on robotic arms. Finally, we address important factors limiting the progress of robotics in cranial neurosurgery.

ROBOTIC SYSTEMS IN CURRENT USE IN CRANIAL NEUROSURGERY

Stereotactic Radiosurgery

The CyberKnife (Accuray, Sunnyvale, CA) represents one of the earliest and most widely used robotic arm systems in cranial neurosurgery. The CyberKnife device comprises a linear accelerator (the radiation source) that is mounted on a robotic arm and an image-guidance system that tracks tumor and patient motion during treatment to realign the treatment beam in real time. After clinical trials beginning in 1994, the CyberKnife received approval by the US Food and Drug Administration (FDA) for treatment of intracranial tumors in 1999. The robotic component of the system is now almost taken for granted because the system has become so ubiquitous, and stereotactic radiosurgery has become so widely accepted as a therapeutic option in contemporary neurosurgery. Even though the system is completely noninvasive, it exemplifies the paradigm of programmable neurosurgical intervention involving real-time sensing and actuation and, to a limited extent, autonomous, on-the-fly control to compensate for small movements.

Trajectory-Finding Robotic Systems

Stereotactic positioning was the earliest application of robotics in neurosurgery, and a number of robotic systems have been devised and used over several decades with this as their principal function. The programmable universal machine for assembly (PUMA; Unimation, Danbury, CT), an industrial robotic arm, was the first robot used in neurosurgical procedures (robot-assisted stereotactic biopsy).[1] The six-degree-of-freedom robotic arm could be mounted to a CT table and positioned with a high degree of precision. The Minerva robot (University of Lausanne, Switzerland) and the NeuroMate robot (Integrated Surgical Systems, Davis, CA) were designed with similar functionality but were purpose-designed for neurosurgical stereotaxy.[2] The NeuroMate represented an extension of work by Alim Louis Benabid at Grenoble University Hospital in the 1980s.[3] It received FDA approval in 1997 and has been used for stereotactic biopsy and depth electrode placement.

In more recent years, two robotic systems have received more widespread use in stereotactic neurosurgical procedures. Zimmer Biomet developed the ROSA ONE robot in 2007. The system has seen increasingly widespread use worldwide in the past decade, and it received FDA approval in 2012 for intracranial use, followed by approval in 2016 for spinal applications (https://paperpile.com/c/6BwSrm/2ctW+40n6+V7Yi).[4–6] It is designed and marketed as an adjunct for stereotactic electrode placement, endoscopy, and tumor biopsy, but has been most widely adopted for stereo-electroencephalography (SEEG), with multiple studies confirming that the system permits safe, accurate, and time-efficient placement of depth electrodes (https://paperpile.com/c/6BwSrm/txjN).[7] The ROSA ONE (Fig. 28.1) has been used in thousands of procedures internationally. Growing adoption of this technology has shifted surgical practices at many large centers toward increased reliance on depth electrodes relative to surface (subdural) electrode arrays in the surgical management of epilepsy. The ROSA ONE is a six-degree-of-freedom robotic arm with a design similar to standard industrial robotic arms. It has a simple end-arm fixture that can position objects and stabilize electrodes or instruments along a trajectory, and it also contains a force sensor. Calibration and positioning software permits the system to calculate trajectories on the basis of preoperative brain imaging. The system is currently limited to high-precision positioning and requires the surgeon to perform all active surgical steps (skin incision, bone drilling, dural incision, advancing to depth along the designated trajectory).

Another notable series of stereotactic positioning robots has been developed by Mazor Robotics, an Israeli medical device company that devised a bone-mounted robotic system predominantly used for spinal instrumentation, but also used for cranial depth electrode placement. Its first robotic guidance system, SpineAssist, received FDA approval in 2004 for spine surgery,[4,5] and the Renaissance Guidance System was approved in 2011. Medtronic (Minneapolis MN) acquired Mazor in 2018 and has helped expand the usefulness of these systems for cranial procedures such as depth electrode placement for deep brain stimulation.[8]

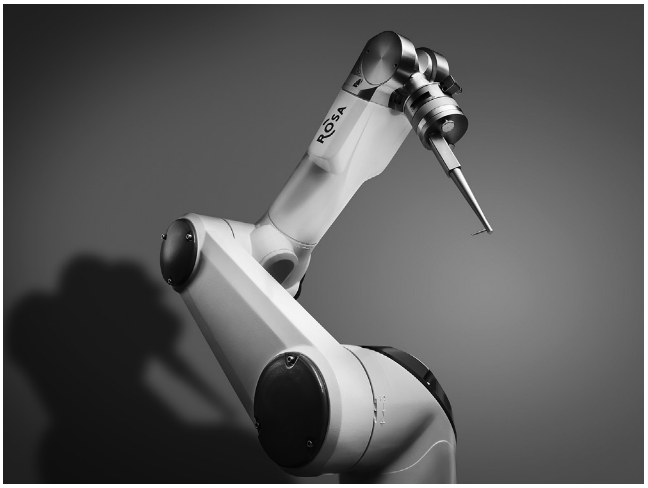

Figure 28.1. The ROSA ONE. The ROSA ONE robotic arm developed by Zimmer Biomet Robotics *(Courtesy LucileBssg/CC BY-SA 4.0. https://en.wikipedia.org/wiki/File:ROSA_One%C2%AE_Robot_.jpg.)*

Notably, these trajectory-finding systems assist in providing increased accuracy and precision, but they rely on the surgeon to perform all key steps by hand; no instruments are actuated under robotic control.

Robotic Micromanipulators with Image Guidance for Tissue Ablation

Building on the success of neurosurgical robotic stereotactic systems, several robotic systems have been developed to perform image-guided tissue ablation.

The NeuroBlate System developed by Monteris Medical (Plymouth, MN) is a tissue ablation platform that uses real-time MRI to monitor probe position and control the depth and directionality of tissue ablation.[9] A bolt fixed to the skull provides a secure mounting point for a robotic manipulator that has essentially two degrees of freedom: probe depth and rotational angle along the probe axis. The system uses MR thermometry to follow the spread of heat in real time, allowing the surgeon to ensure precise, region-specific tissue ablation.

The Visualase MRI-guided laser ablation system (Medtronic) has also been used in conjunction with robotic stereotaxy platforms, including the ROSA ONE, to add tissue ablation capabilities to a robotic system that is otherwise designed for stereotactic positioning.[10]

Dexterous Neurosurgical Robotics

Stereotaxy and ablation systems involve multiple-degree-of-freedom robotic arms and integrated imaging and software capabilities, but the functionality of these systems has been limited because of the simplicity of their end effectors; tools mounted on the arms have typically been passive, or at least not capable of dexterous movement. Within neurosurgery proper, the availability of dexterous surgical robots has been limited. One major exception has been the NeuroArm (Fig. 28.2). The NeuroArm and its successor

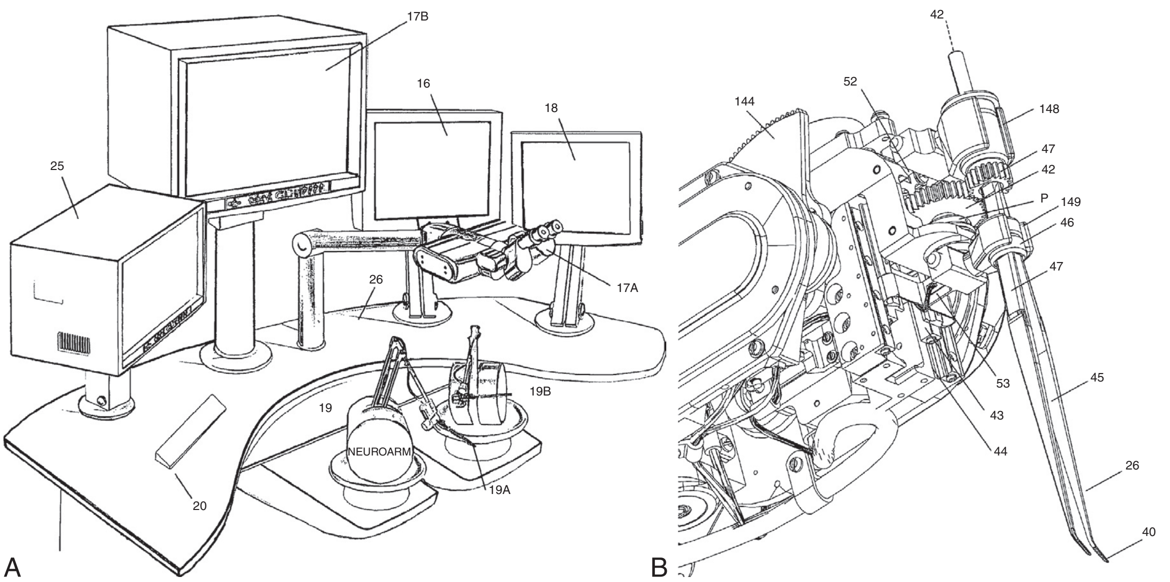

Figure 28.2. The NeuroArm. (A) Control console for the NeuroArm robotic system, including monitors and surgical microscope objective, as well as bimanual micromanipulators. (B) End effector for the NeuroArm instrumented as forceps. *(From Sutherland GR, Louw DF, McBeth PB, Fielding T, Grogoris DJ, inventors; Microbiotics Corporation, Calgary, Canada, assignee. Microsurgical robot system. US Patent No. 7,155,316 B2. December 26, 2006.)*

Figure 28.3. The Da Vinci robot. The Da Vinci surgical robotic system enables surgeons seated at consoles separate from the main sterile field to control a multi-arm robot performing a multiport surgery. At least one robotic arm typically holds a camera providing a view of the operative field (as shown on the screen in the image). An assistant remains sterile and is able to exchange instruments and physically manipulate the robotic arms as needed. *(Courtesy Intuitive Surgical, Sunnyvale, CA.)*

systems through several generations, now part of the SYMBIS system (IMRIS Inc., Minnetonka, MN), were originally developed by the University of Calgary under the leadership of neurosurgeon Garnette Sutherland with engineers from MacDonald, Dettwiler and Associates. This system is the first image-guided, MRI-compatible neurosurgical robot, and it is capable of microneurosurgery as well as stereotaxy. The system comprises two remote, detachable manipulators on a mobile base. Piezoelectric motors and other MRI-compatible components allow for the system to minimize image artifacts while in operation, and three-dimensional force sensors provide precise haptic feedback to the operating surgeon.[11,12] By 2013 the device had been used in over 35 human cases of graded complexity, and in 2015 its successor, the SYMBIS Surgical System, received FDA approval.[13,13a] It has now been cleared for use in various neurosurgical procedures including resection of cavernous malformations, brain tumors, and radiation necrosis.[14–16]

Advanced Robotic Surgical Systems Used Primarily in Other Specialties

Several advanced surgical robotic systems have been developed for fields outside neurosurgery. These include the Da Vinci robotic system (Intuitive Surgical), the HEARO system (Heathkit, Ottsville, PA), RobOtol robots designed for neuro-otology, and the Corrindus and Robocath systems for robotic vascular intervention. Technological progress in these allied fields is interpreted by some as an indicator of likely future developments in neurosurgical robotics.

A suite of robotic systems developed by Intuitive Surgical over the past two decades have transformed some aspects of general surgery, urology, colorectal surgery, head and neck surgery, cardiothoracic surgery, and gynecology. The Da Vinci robotic systems are best known as multi-armed robots that permit surgeons to operate single-port or multiport robotic systems from a remote console, with bimanual control and stereoscopic vision of the operative field (Fig. 28.3). These robots are designed to facilitate surgical workflows similar to those developed for single- or multiport laparoscopy, and a range of end effectors can be mounted on each robotic arm, permitting endoscopic visualization, suturing and stapling, thermocautery, and a range of specialized functions, all under real-time control by the surgeon, aided by motion scaling and tremor reduction. While autonomous modes of operation are not presently available, some basic real-time decision support functions are available, with instrument collision detections and related warnings displayed to the surgeon and operative staff. Although there are no approved indications for neurosurgical use of the Da Vinci systems, their instruments or the Da Vinci platform as a whole have been used for minimal access cranial surgery in a research setting[17,18] and have been used off-label in a number of small case series, typically in collaboration with otorhinolaryngologic surgeons in approaching the skull base and upper cervical spine in transoral procedures,[19–22a] including resection of cystic sellar lesions and of the odontoid process. There is at present an immense worldwide experience with the Da Vinci systems, and their capabilities continue to expand.

Two groups have gained traction in developing robotic approaches to accessing the scala tympani for the placement of electrode arrays during cochlear implant surgery. The HEARO is a cochlear-accessing robotic arm that has been developed collaboratively by Cascination AG and the Insel Hospital. The system received a CE mark (Conformité Européene) in 2020.[23–25] This system enables a minimally invasive, high-precision approach to the cochlea by optimizing trajectory angles. The device was used for successful implantation in 6 of 9 patients in a recent trial, with reversion to the conventional approach in 3 patients because of safety considerations.[26] The RobOtol is a robot-assisted device that increases the precision of electrode placement within the cochlea and minimizes insertion-related trauma to the middle ear.[27,28] This is primarily achieved by allowing for insertion speeds lower than manual insertion, which is limited by natural hand tremors.[29–31] The device received a CE mark in 2016. Safe and reliable insertion has consistently been achieved, with recent clinical studies showing significantly reduced trauma.[32–36]

The CorPath GRX Robotic system is currently approved for percutaneous coronary and peripheral vascular interventions. Although originally designed for peripheral vascular surgery, the system has undergone a number of modifications to facilitate the use of smaller microcatheters and microwires to facilitate intracranial interventions in the future. The system is operated from a remote workstation, where an interventionist sits at a mobile, radiation-shielded console that houses the navigational control software. By manipulating three joysticks, the interventionist is able to conduct robot-assisted manipulation and advance, retract, and deploy endovascular devices (catheters, guidewires, stent systems, and coiling systems) as needed. A tableside unit holds the robotic arm, drive system, and a single-use procedural cassette. The system requires manual setup to establish arterial access and place the guide catheter. Following initial setup, the workstation software, robotic arm, and cassette function together under the guidance of the operator. These microcatheter-based techniques can potentially be used for cerebrovascular interventions, but further hardware and software development will be required. To date, neuroendovascular applications have been limited to carotid stenting.

Robot-assisted endovascular treatment of stroke has received substantial attention for a variety of reasons, including the prospect of enabling the proceduralist to operate remotely in emergent settings, which may facilitate more rapid intervention. In addition to the CorPath system (Corrindus), the R-One system developed by Robocath, currently approved for percutaneous coronary intervention,[37,38] is being optimized for stroke intervention, including through development of algorithms for navigation of a neurovascular catheter.[39]

PRINCIPLES OF ROBOTICS RELEVANT TO SURGERY

Several principles and themes guide the development of robotic systems in general, and surgical robotics in particular. A major advantage to robotic systems relates to their ability to move and execute tasks with accuracy and precision, reliably and repeatedly without fatiguing, at potentially at high speeds. Robots are programmable machines, and as a result their responses to anticipated scenarios should be highly predictable. To a large degree, the ability to program robotic systems depends on feedback data obtained from sensors. Sensor data may take many forms, including video feeds from cameras mounted on an arm or the main body of the robot, sensors monitoring joint angles and positions, and force-feedback sensors detecting load on various parts of the robot (especially the load at the end of the arm). Simple robots can execute highly repeatable programs in a feed-forward manner (making a prescribed set of precise actions over and over again). Although this type of behavior can at times be useful, it is the ability to integrate sensor information in feedback control loops that enables robotic systems to be situationally aware, adaptable, and responsive to individual situations. Autonomous actions by robots in all but the most controlled and predictable environments are dependent on the integration of sensor data. Haptic feedback, a sense of simulated touch transmitted to the surgeon operating a robot, is of special interest in surgical robotics and remains an area of active research and development; at present, only a small minority of surgical robotic systems integrate haptic feedback, and most are guided on the basis of visual input alone.

The usefulness of robots in general and surgical robots in particular is highly dependent on the end effectors; for many robots, these end effectors are the tools mounted on the end of the robotic arms. The mechanical and electrical systems, sensor systems, and computing systems are all designed to deliver and control the actions of the end effector. The simplest surgical robots have minimalist end effectors, such as completely passive stabilizing sleeves used only for stereotactic guidance. More advanced systems, including the Da Vinci systems, contain versatile arms that are capable of operating a variety of tools that may be swapped in and out over the course of an operation, all controlled with standardized actuating mechanisms.

LIMITATIONS OF CURRENT NEUROSURGICAL ROBOTIC SYSTEMS

While many surgical fields have benefited from the advent of dexterous robotic systems, neurosurgery has lagged behind by comparison, with a variety of stereotactic robotic systems available but a lack of functionality in end effectors beyond ablation. Progress in neurosurgical robotics has been limited by several factors: the need to remove bone, the importance of haptic feedback when manipulating extremely delicate tissue, and the comparatively small size of the neurosurgical market relative to others in the context of technology development driven predominantly by industry. The often small size of the operative corridors in cranial neurosurgery also necessitates small-caliber robotic trocars. None of these factors is fundamental—developments in robotic technology are on a trajectory toward increasing influence in neurosurgery.

FUTURE DIRECTIONS AND NEEDS FOR FUTURE SYSTEMS

Robotic surgery in many ways represents a logical progression from laparoscopic and endoscopic surgery, and robotic systems have borrowed their form factors and workflows in many cases from these areas of minimally invasive surgery. The Da Vinci surgical system exemplifies this paradigm, with robotic arms that support positioning and manipulation of port-based tools and port-based cameras that provide endoscopic views of the surgical field. Endoscopic techniques became standard in neurosurgery one to two decades or more after being adopted and developed in specialties such as general surgery, urology, colorectal surgery, otorhinolaryngology, and thoracic surgery. The development of neurosurgical robotics has also lagged behind the development of robotic techniques in other surgical specialties.

Excellent haptic feedback, small instruments capable of microsurgical soft tissue management, high-precision image guidance and instrument tracking, and tools for bone removal are all required for progress in neurosurgical robotics.

Neurosurgical robotics, like neurosurgical endoscopy, requires microsurgical instruments operating through small trocars. With the limited exceptions of the air-filled nasal cavity as a corridor to the skull base and the fluid-filled ventricular system as a corridor to certain deep brain structures, operative corridors in cranial neurosurgery are tightly constrained by bone and by the brain itself in ways that cannot always be solved by direct retraction or insufflation, techniques that facilitate laparoscopic techniques elsewhere in the body.

The need to remove bone in a controlled fashion is also an important consideration in neurosurgery that is not adequately addressed by existing robotic systems. This need is not unique to neurosurgery, as maxillofacial and orthopedic surgery share the need to drill and shape bone. There is ample precedent in industrial machining processes for solid milling tools capable of operating safely at high precision, so there is reason to believe that a future generation of robots will be capable of safe bone removal.

Programmable control of surgical robots offer the possibilities not only of technical improvements in surgery through techniques such as scaling down movements and reducing tremor, but also of monitoring sensor data, providing decision support, and using modern machine learning techniques to collect operative data from many surgeons, ultimately to augment and, at times, replace the human surgeon as robotic systems develop over time. From the standpoint of machine learning and artificial intelligence, many technical problems in high-performance surgery are analogous to problems in autonomous driving, a major difference being that there are vastly more data available to the automotive industry.

This is a forward-looking chapter covering an emerging area in cranial neurosurgery. By the time the current edition is in circulation, some of the material presented here will likely be obsolete, and the next edition of this textbook will likely present substantial progress in the field of cranial neurosurgical robotics. The era of robotic neurosurgery has arrived.

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