The American Journal of Surgery

The American Journal of Surgery 188 (Suppl to October 2004) 68S–75S

# Robotics in neurosurgery

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**Abstract**

Technological developments in imaging guidance, intraoperative imaging, and microscopy have pushed neurosurgeons to the limits of their dexterity and stamina. The introduction of robotically assisted surgery has provided surgeons with improved ergonomics and enhanced visualization, dexterity, and haptic capabilities. This article provides a historical perspective on neurosurgical robots, including image-guided stereotactic and microsurgery systems. The future of robot-assisted neurosurgery, including the use of surgical simulation tools and methods to evaluate surgeon performance, is discussed.

*Heavier-than-air flying machines are impossible.*

—Lord Kelvin (William Thomson), Australian Institute of Physics, 1895

Neurosurgeons, constrained by their anthropomorphic design, may have reached the limits of their dexterity and stamina. The combination of magnification of the operative field and tool miniaturization has overwhelmed the spatial resolution of the adult human hand. Robots, in contrast, are capable of minute, tremor-filtered movements and are indefatigable. These assets are invaluable in any microsurgical arena, particularly when manipulating delicate and diseased intracranial structures. Recent advances in processor power and imaging systems provide digitized encoding of detailed spatial data to guide new generations of neurosurgical robots. When coupled with multidimensional haptics, they will complete the transition of surgery from the Industrial Age to the Information Age [1].

## Neurosurgical robotics review

The first reported use of a robot in neurosurgery was in 1985 by Kwoh and colleagues [2], who employed a Programmable Universal Machine for Assembly ([PUMA]; Advanced Research Robotics, Oxford, CT) industrial robot for holding and manipulating biopsy cannulae. Although the robot served only as a holder/guide, the potential value of robotic systems in surgery was evident. In 1991, Drake and coworkers [3] reported the use of a PUMA robot as a retraction device in the surgical management of thalamic astrocytomas. Despite their novel application, both systems lacked the proper safety features needed for widespread acceptance into neurosurgery. Beginning in 1987, Benabid and associates [4] experimented with an early precursor to the robot marketed as NeuroMate (Integrated Surgical Systems, Sacramento, CA). NeuroMate uses preoperative image data to assist with surgical planning and a passive robotic arm to perform the procedure. The NeuroMate system has been used in >1,000 cases.

These first neurosurgical robots relied on preoperative images to determine robotic positioning. As a result, surgeons could not dynamically monitor needle placement under image-guidance and were blind to changes such as brain shift. To satisfy the need for a real-time, image-guided system, Minerva was developed (University of Lausanne, Lausanne, Switzerland). The system consisted of a robotic arm placed inside a computed tomography (CT) scanner, thus allowing surgeons to monitor the operation in real-time and make appropriate adjustments to the trajectory as needed [5].

Despite considerable engineering challenges, the design and construction of magnetic resonance (MR)–compatible robotic systems soon followed. MR compatibility ensures that the robot produces minimal MR imaging (MRI) artifact and that the operation of the robot is not disturbed by the

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doi:10.1016/j.amjsurg.2004.08.004

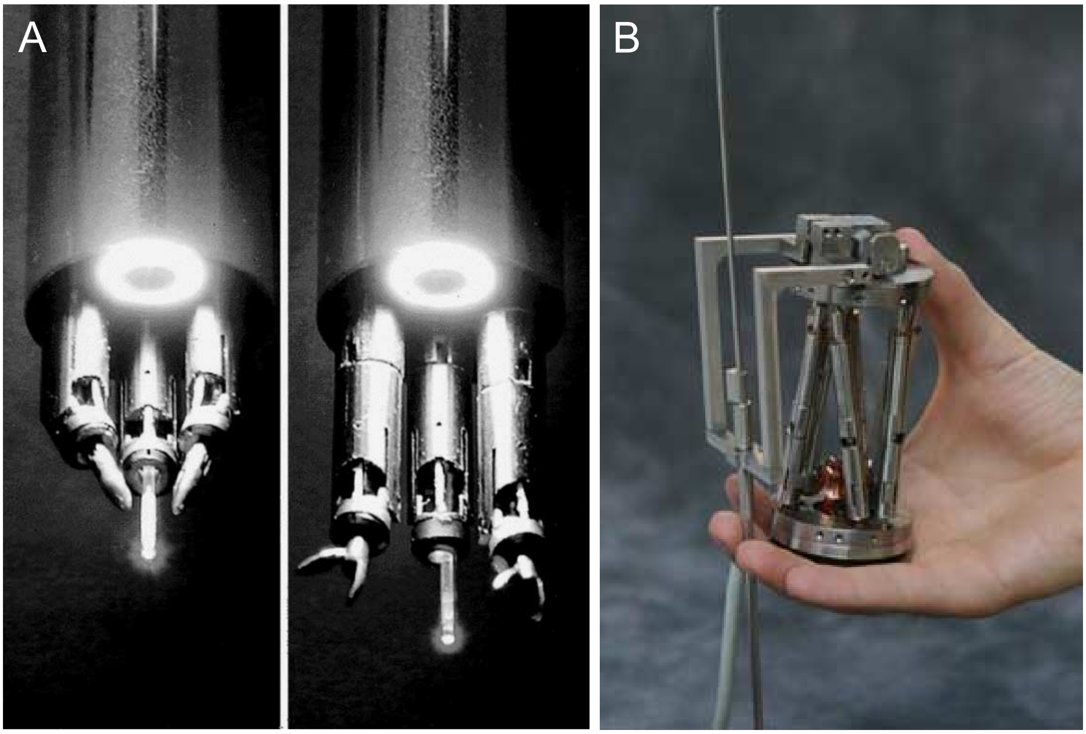



Fig. 1. Surgical robotic systems. (*A*) NeuRobot (Shinshu University School of Medicine, Matsumoto, Japan) (image courtesy of K. Hongo). (*B*) SpineAssist (Mazor Surgical Technologies, Haifa, Israel) (image courtesy of M. Shoham).

electromagnetic fields. Proper material selection is critical to avoid adverse effects on image distortion or changes in contrast and signal-to-noise ratio (SNR). The benefits of MR soft-tissue visualization nevertheless prompted investigators from Harvard University (Cambridge, MA) [6], the University of Tokyo (Tokyo, Japan) [7], and the University of Calgary (Calgary, Alberta, Canada) [8] to develop their own MR-compatible robotic systems.

The majority of time in neurosurgical cases is spent on micromanipulation. However, most neurosurgical robotic systems perform only stereotactic procedures. The Robot-Assisted Microsurgery System (RAMS) [9] and the Steady Hand [10] projects have, however, developed robotic systems for enhanced tool manipulation. RAMS was developed by the US National Aeronautics and Space Administration (NASA; Washington, DC) to provide a dexterous platform to perform surgery at increased precision. The system is based on master-slave control; the motion of a slave arm with 6 degrees of freedom is linked to the motion of a haptic hand controller, which also has 6 degrees of freedom. RAMS is equipped with adjustable tremor filters and motion scalers to enhance dexterity [11]. A feasibility study of microvascular anastomosis in neurosurgery was conducted by Le Roux and colleagues [12]. Carotid arteriotomies were performed in 10 rats and subsequently repaired by surgeons, students, engineers, and RAMS. Within the surgical group RAMS was as effective in achieving vessel patency, but took nearly twice the time [12].

The Steady Hand system developed at Johns Hopkins University (Baltimore, MD) is another dexterity-enhancement system designed to augment microsurgery by filtering tremor [10]. The operator's hand manipulates tools connected to and controlled by a robotic arm. The tools have strain gauges in their handles to detect force. The robot controller measures the incoming forces and filters tremor. Despite its novel design, the system has not been used in clinical applications.

In Japan, Hongo and colleagues [13] developed a robot platform for telecontrolled microneurosurgery through the portal of an endoscope (Fig. 1A). The robot is based on a 10-mm endoscope equipped with twin tissue forceps, a camera, a light source, and a laser. Investigators performed neurosurgery on a cadaveric head and concluded that the system facilitated more accurate and less invasive surgery [13]. NeuRobot (Shinshu University School of Medicine, Matsumoto, Japan) was subsequently used to remove a portion of a tumor from a patient with a recurrent, atypical meningioma [14].

Surgical robotic systems are also used for spinal applications. The SpineAssist robot (Mazor Surgical Technologies, Haifa, Israel) was recently awarded US Food and Drug Administration (FDA) approval for use in spinal surgery (Fig. 1B). The system, which is no larger than a soda can, is designed to attach directly to the patient's spine—acting as a guide for tool positioning and implant placement. It includes sophisticated software for image guidance, permitting reduced invasiveness of surgical procedures. It also has nonspinal orthopedic applications [15,16].

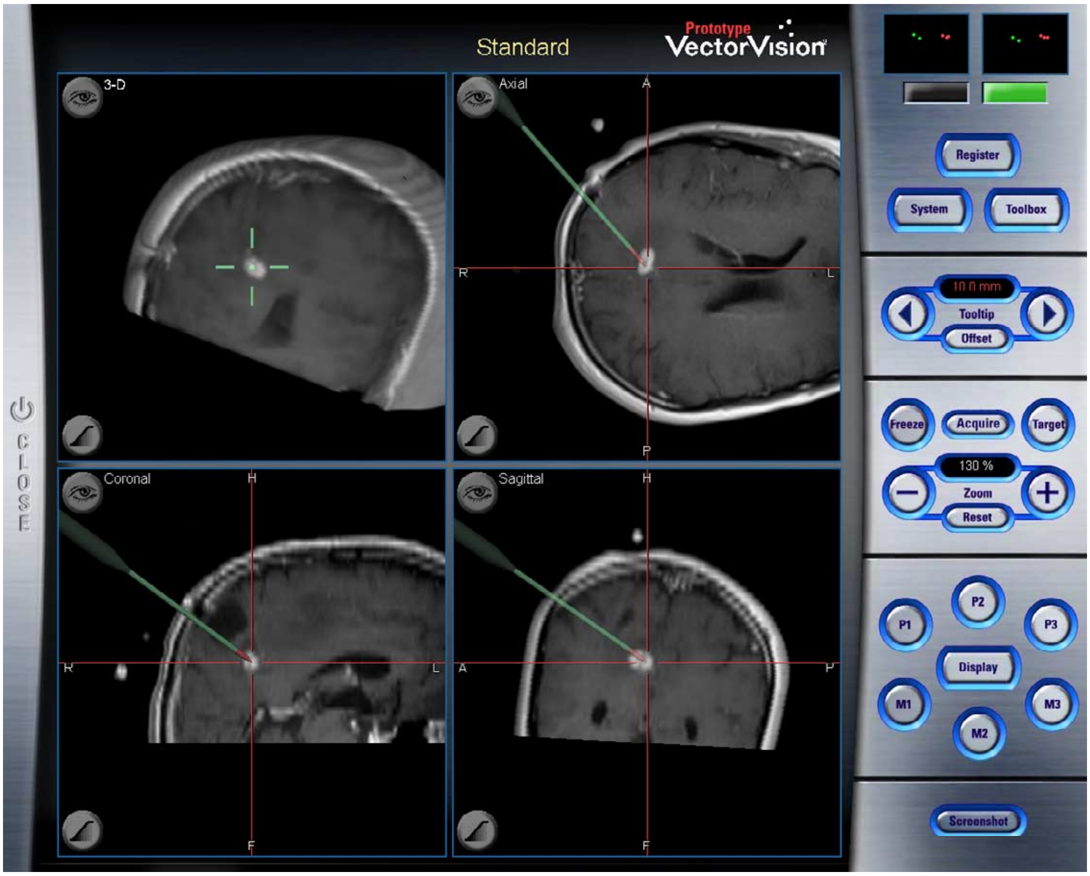



Fig. 2. Screen capture of multiplanar gadolinium-enhanced T1-weighted intraoperative magnetic resonance images showing trajectory planning. 3D = 3-dimensional.

## Imaging technologies

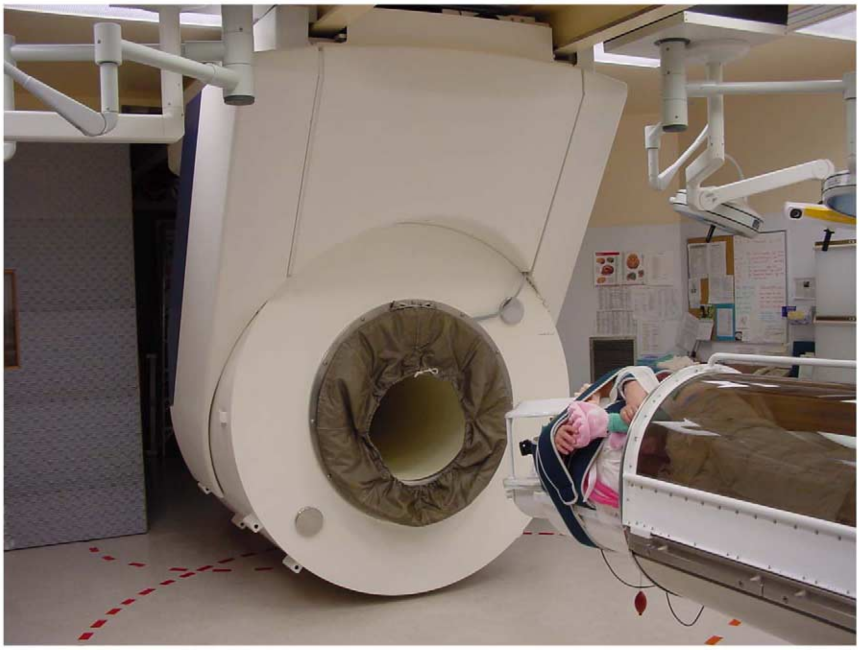
### *Image-guided surgery*

The development of CT by Hounsfield in 1973 [17] and MRI by Lauterbur [18] and Mansfield and Grannell [19] in the 1970s significantly improved the lesion localization capabilities of neurosurgeons. These imaging modalities provide the ability to depict pathology and determine its 3-dimensional location within the cranium. Coupling these technologies with computer-aided neuronavigation tools has augmented preoperative lesion localization, permitting more precise craniotomies and surgical corridors.

Computers were first used in the early 1970s to stereotactically locate deep-brain structures and lesions [20,21]. Goerss and coworkers [22] continued these developments in the early 1980s by creating software programs for calculation of stereotactic coordinates in the operating room and applying them to well-established, frame-based stereotactic techniques. These pioneering efforts resulted in frameless stereotaxy, a technique allowing real-time localization of surgical instrumentation in corresponding (archived) images of the patient. Frameless navigation subsequently became widely accepted in cranial and spinal surgery applications and is now considered standard, not experimental (Fig. 2). These techniques rely on correlating the position of surface-mounted fiducial markers on the skull with the position of reference points on the head frame, providing a mathematical relation between the intracranial image data and the patient. The 3-dimensional position of fiducial markers and surgical tools is determined using a localization device based on electromechanical (digitizing arm), electromagnetic, optoelectronic, or ultrasound technology. Using these techniques, it is possible to determine the position and orientation of surgical tools, such as biopsy needles, in relation to the intracranial image data.

### *Intraoperative imaging*

Traditionally, neurosurgical navigation has relied on preoperative images and the assumption that anatomical structures of interest remain in the same position with respect to each other and the fiducial markers used for registration. During surgery, however, tissue deformation and shift disrupt the spatial relation between the patient and the preoperative image volumes, resulting in localization errors. Intraoperative imaging techniques appear to be the best approach to counter these problems. Thus, 3-dimensional



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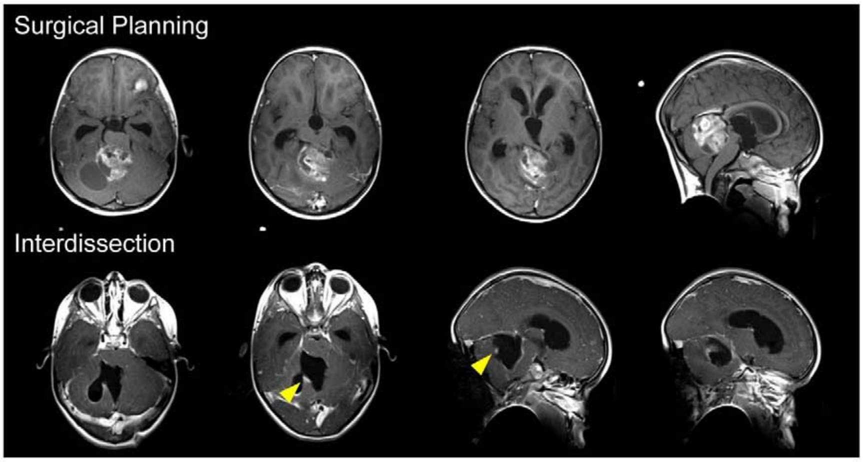


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Fig. 3. (*A*) Operating room equipped with a ceiling-mounted 1.5-T intraoperative magnetic resonance imaging system and surgical navigation system. (*B*) The interdissection (intraoperative) image shows a tumor that is cryptic to the microsurgeon, facilitating the complete removal necessary for cure.

ultrasound, CT, and MRI have been introduced to compensate for intraoperative changes and residual tumor and to update navigation registration [23–28].

The development and integration of intraoperative MRI (iMRI) systems into the operating room has provided a major advance in neurosurgery. Surgeons no longer solely rely on preoperative diagnostic scans to navigate the brain. Instead intraoperative imaging provides surgeons with updated MR images that allow for assessment of brain shift, evaluation of tumor resection, exclusion of hematoma, and identification of ischemic brain [29]. The Harvard group, using a 0.5-T vertical open-configuration system, pioneered these developments [30].

We have developed a novel iMRI system that is capable of providing high-quality intraoperative images (Fig. 3). The system is integrated into a well-established surgical environment and has been used in >550 neurosurgery cases and 6 hepatic thermal ablation procedures since 2003. Intraoperative images are produced using a moveable 1.5-T magnet [23,29]. The magnet is mounted on ceiling rails and moves in and out of the operating room when required. The portability of the magnet allows for preoperative, interdissection, and quality-assurance scans while maintaining the focus on the patient and surgeon. It also permits the use of traditional, non–MRI-compatible microscopes and drills, which are merely moved beyond the 5-G line during imaging. The higher field strength ensures rapid image acquisition, at a spatial resolution comparable to the diagnostic images, as well as excellent MR angiography.

A next-generation iMRI system is currently in its preliminary stages of development at the University of Calgary. This new system will include high-speed gradients capable of standard, spectrographic, and functional imaging, as well as a wider bore to accommodate safe robotic interventions of the brain, breast, liver, lung, and prostate.

## NeuroArm prototype

Specialized neurorobotic systems have been developed for performing well-defined tasks, such as image-guided biopsies or haptic-enhanced, motion-scaled microsurgery. Currently, however, no robot exists that packages these important features into a single stable platform for clinical trials and academic research. Construction of neuroArm (University of Calgary, Calgary, Alberta, Canada) will result in a unique, MR-compatible, haptic platform capable of performing a full spectrum of neurosurgical procedures [8] (Fig. 4).

NeuroArm consists of a robot, a controller, and a workstation. The system is based on master-slave control in which commanded hand-controller movements are replicated by the robot arms. The workstation provides visual, audio, and tactile feedback, creating an immersive environment for the surgeon. Recreating the usual surgical environment in this way will aid adaptation to this new technology. A binocular display provides stereoscopic views of the surgical worksite, and desk-mounted displays provide MR images, robot parameter updates, and various views of the surgical worksite. Tools will be superposed on the MR images, providing real-time visual feedback for intracranial procedures.

NeuroArm will perform standard techniques such as biopsy, microdissection, thermocoagulation, and fine suturing. Procedures such as lesionectomy and aneurysm clipping will be possible. The robot was designed to replicate the way that surgeons position themselves and their tools during surgery (a process known as biomimicry). It consists of 2 arms, each with 7 degrees of freedom for precise tool positioning, and a 1-degree-of-freedom tool actuation mechanism for each end-effector. Both arms are secured on a vertically adjustable mobile base. The mobile base is positioned adjacent to the operating room table and is mechanically secured using wheel brakes. For microsurgical procedures, standard tools such as bipolar forceps, needle drivers, suction, microscissors, and microdissectors were designed to fit the end-effector. For stereotactic procedures, a linear drive mechanism was designed to provide accurate targeting via a cannula and introducer. The robot end-effector is equipped with a unique tool-actuation mechanism, as well as a multiaxis force sensor system to provide haptic force feedback to the surgeon. The spatial constraints and force cross-coupling effects caused by the miniaturization of multiarticulating end-effectors have complicated the development of high-fidelity multiaxis force sensors. Nevertheless, there have been significant developments in haptic hand-controller design, and several commercially available systems such as the Phantom (Sensible Technologies, Boston, MA) are now available.

NeuroArm is designed for deployment within an MR magnet bore for stereotactic procedures (Fig. 5). During stereotaxy, real-time MR images provide image guidance and improve tool positioning, ensuring that significant samples are extracted during biopsies. The feasibility of using neuroArm to perform microsurgery inside the magnet bore will be examined. If it proves reliable and safe, this configuration will allow the surgeon to view continuously updated MR images to ensure that the entire lesion has been removed. The current design of neuroArm permits image-guided microsurgery, which requires registration of preoperative MRI data to skin-mounted fiducial markers. This is accomplished using a mechanical digitizing arm attached to the robot base. The systems-controller computers will therefore always know the position of the tool tips in relation to the surgical target, which is outlined with a computer mouse–based cursor on the MRI during presurgical planning. This permits the ability to program "no-fly" or "no-go" zones before the procedure commences, protecting normal brain tissue from injury in the event of unskilled or accidental movement of the hand controllers.

Material and component selection is critical for MR compatibility. Samples of all robot construction materials have been through MR testing to evaluate their effect on image distortion and changes in contrast and SNR. Various structural materials, including aluminum, titanium, carbon and glass composites, and plastics, were evaluated. Material tests indicate that titanium and plastic had the smallest effect on MR image quality reduction. As a result, the proximal and distal arm structural components are made of titanium and PEEK (polyetheretherketone), respectively. The actuators and encoders were also tested for MR compatibility and found to have minimal effect.

## Future directions

### *Surgical simulation*

Surgical simulation involves performing surgical procedures inside a virtual environment that may include visual, audio, tactile (haptic), or other feedback. It allows apprentice surgeons to practice procedures in a safe environment, permits performance evaluation, and provides active surgeons with a means to rehearse difficult cases in a risk-free environment.

The neuroArm workstation will double as a sophisticated surgical simulator (Fig. 6). The immersive environment digitally fashioned by the workstation controller during robotic surgery will be applied to virtual surgery. Ongoing improvements in models of brain biophysical properties, tool-tissue interaction, realistic rendering of hemorrhage, and co-registration with universal brain atlases and multimodal imaging will make virtual surgery performed at the

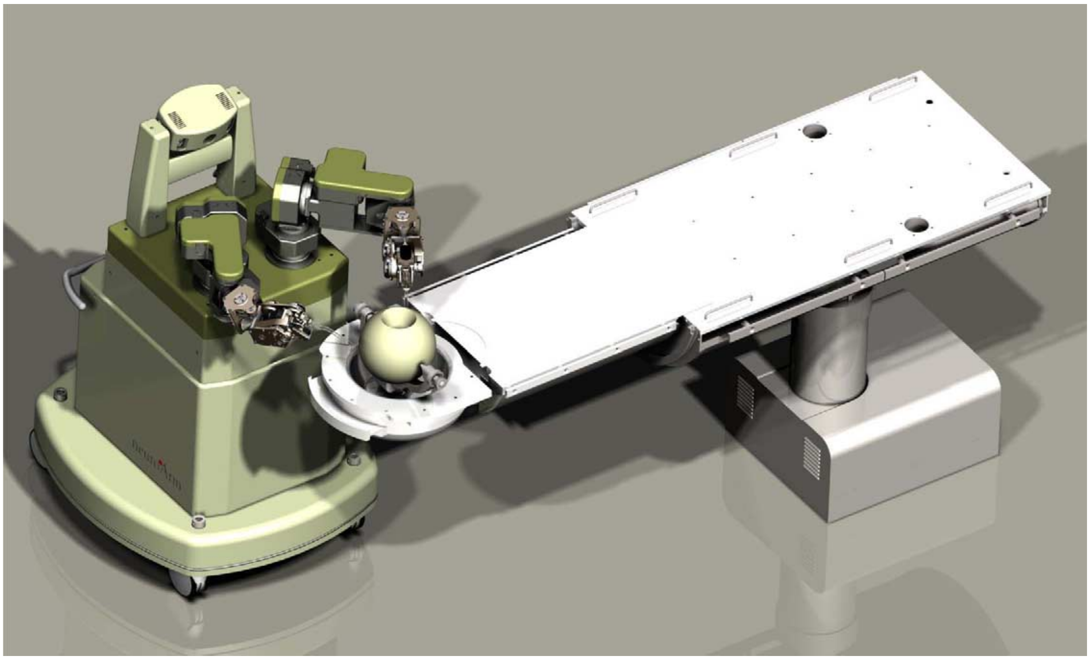

Fig. 4. NeuroArm (University of Calgary, Calgary, Alberta, Canada) in position for microsurgery. At this stage of the procedure the surgical microscope (not shown) is positioned adjacent to the robot base.

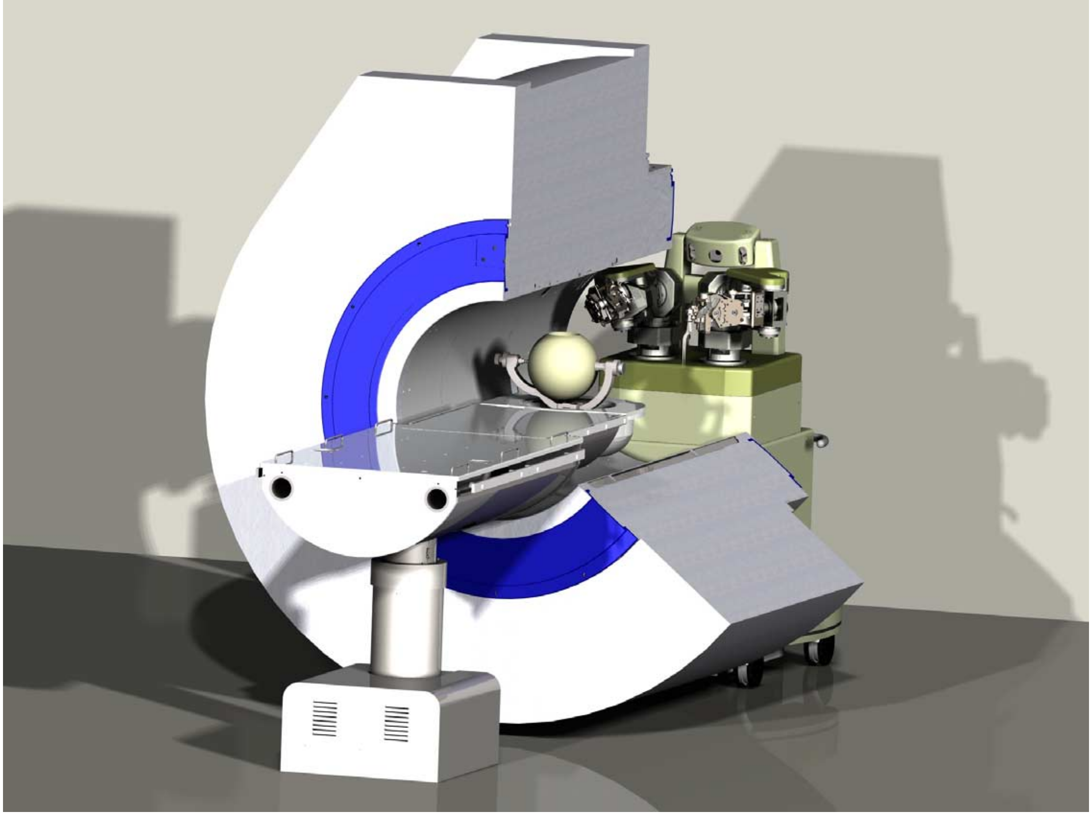

Fig. 5. NeuroArm (University of Calgary, Calgary, Alberta, Canada) in position for stereotaxy. The base is equipped with an extension platform (not shown) that allows the manipulator arms to reach inside the magnet bore.

workstation less distinguishable from reality. Initially, only a limited number of procedures will be simulated, but as neuroArm is used for an ever-expanding number of operations, more detailed data will become available. Patient-specific modeling and simulation will be accomplished by importing MRI data into the simulation program. It is also


Fig. 6. A neuroArm workstation (University of Calgary, Calgary, Alberta, Canada).

our intention to simulate conventional, nonrobotic neurosurgery. The haptic hand controllers will have removable end pieces that are structured after standard neurosurgical tools. For example, haptic-enabled forceps installed on the hand controllers would be used to simulate the fine suturing of blood vessels.

### *Surgical performance and certification*

Surgical training programs are moving toward a more structured curriculum in which physical models and simulators will play a more important role in developing surgical skill and in evaluating and certifying trainees. To increase the acceptance and integration of simulators into training programs, it is important to show that time spent on simulators can actually supplement operating-room experience.

There is a need for objective methods to evaluate surgical performance, as current methods of evaluation are mainly subjective and potentially unreliable [31]. To a large extent, resident training has been based on an apprenticeship model in which individual surgeons graduate from simple to more complex tasks [32]. Although this has thus far been a reasonable approach, the introduction of increasingly sophisticated surgical technologies, together with decreased individual case volume, suggests the benefit of additional training methods. Several general surgery groups are working to develop methods to objectively evaluate surgeon performance during minimally invasive surgery [33,34], but little has been done with regard to neurosurgery. To ameliorate this problem, our group has used an optoelectronic tracking technique based on tool-tip kinematics to quantitatively evaluate neurosurgeon performance. Initial results for a microvascular anastomosis paradigm suggest that an experienced surgeon performs specific tasks consistently from animal to animal and that selected performance measures are only slightly affected by task variability. Speed of the procedure and tool-tip velocity do not predict patency rates as well as tool-tip excursion amplitude. The use of position and force data recorded from haptic-enabled surgical robotic devices will enhance detailed quantitative evaluation of surgeon performance [4].

## Summary

Technological developments in imaging guidance, intraoperative imaging, and microscopy have pushed neurosurgeons to the limits of their dexterity and stamina. The introduction of robotically assisted surgery has provided surgeons with improved ergonomics and enhanced visualization, dexterity, and haptic capabilities. The future of robot-assisted neurosurgery will include the enhanced use of surgical simulation tools and objective methods to evaluate surgeon performance.

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