Progress in Neurosurgical Robotics

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Technology in Neurosurgery

Historically, progress in neurosurgery has paralleled technological innovation. This trend began with improved neurosurgical instrumentation. In 1927, Bovie and Cushing revolutionized neurosurgery with the introduction of electrocautery [1]. For the first time, neurosurgeons were provided a technology that could control bleeding, resulting in a substantial reduction of operative morbidity and mortality. The ability to achieve hemostasis also allowed surgeons to begin surgically managing lesions that were previously considered inoperable.

Around this time, visualization of the surgical site evolved from the incandescent head lamp, progressing into today's counterbalanced operating microscope [2]. Magnification of the surgical field initiated the microsurgical paradigm, with narrower surgical corridors and greatly enhanced visual differentiation between normal and pathological tissue. The resulting microsurgical revolution necessitated the creation of increasingly small, precise surgical instrumentation [3].

Prior to the twentieth century, surgical localization was based on the principles of Paul Broca and contemporaries, who established concepts of cortical compartmentalization of function based on clinical pathological correlation [4]. In 1895, Wilhelm Conrad Roentgen revolutionized diagnostic medicine with the discovery of X-rays [5]. This was improved upon by the serendipitous discovery of pneumoencephalography, or air injection, in 1917, which visualized brain shift through displacement of ventricles [6]. Pneumoencephalography remained the primary neurological imaging modality until the mid-1950s, when contrast angiography became widespread because of decreased toxicity of contrast agents. The invention of the microprocessor allowed for the explosive growth of computer technology, which, when coupled with X-ray imaging, created computerized tomographic imaging (CT) in the early 1970s [7]. Characterization of electron spin in the hydrogen atom was also coupled to computer technology to create magnetic resonance (MR) imaging [8, 9]. These technologies allowed serial 2D imaging of the human body and accurate lesion localization within a particular 2D plane. Volumetric reconstruction followed, presenting interactive 3D virtual models, from which additive or destructive lesions on the brain could be observed. In addition, MR technology evolved to allow imaging of brain function and metabolism [10, 11].

The explosive growth of imaging technology contributed to a new paradigm in surgery: one of minimalistic technique. Rapidly developing technologies merged in the operating room, equipping the surgeon with an array of new instrumentation including endoscopy, high-definition cameras, computer displays, and elongated tools capable of accessing body compartments through small portals. It was very quickly shown that minimalistic surgical technique resulted in decreased length of hospital stay, lower rates of surgical complication, improved patient outcome, and increased patient satisfaction [12, 13].

In addition, as intracranial operations involve fixed anatomy in a contained volume, investigators began to exploit triangular geometry to link preoperative images with intraoperative surgical navigation [14, 15]. As a result, cranial openings became smaller, and surgeons were able to accurately target deep brain pathology using patient-specific imaging. Unfortunately, the act of surgical dissection results in brain shift, whether through anesthetic management, patient positioning for surgery, drainage of cerebral spinal fluid, progressive excision of pathology, or brain edema. In response to this challenge, several investigators began to

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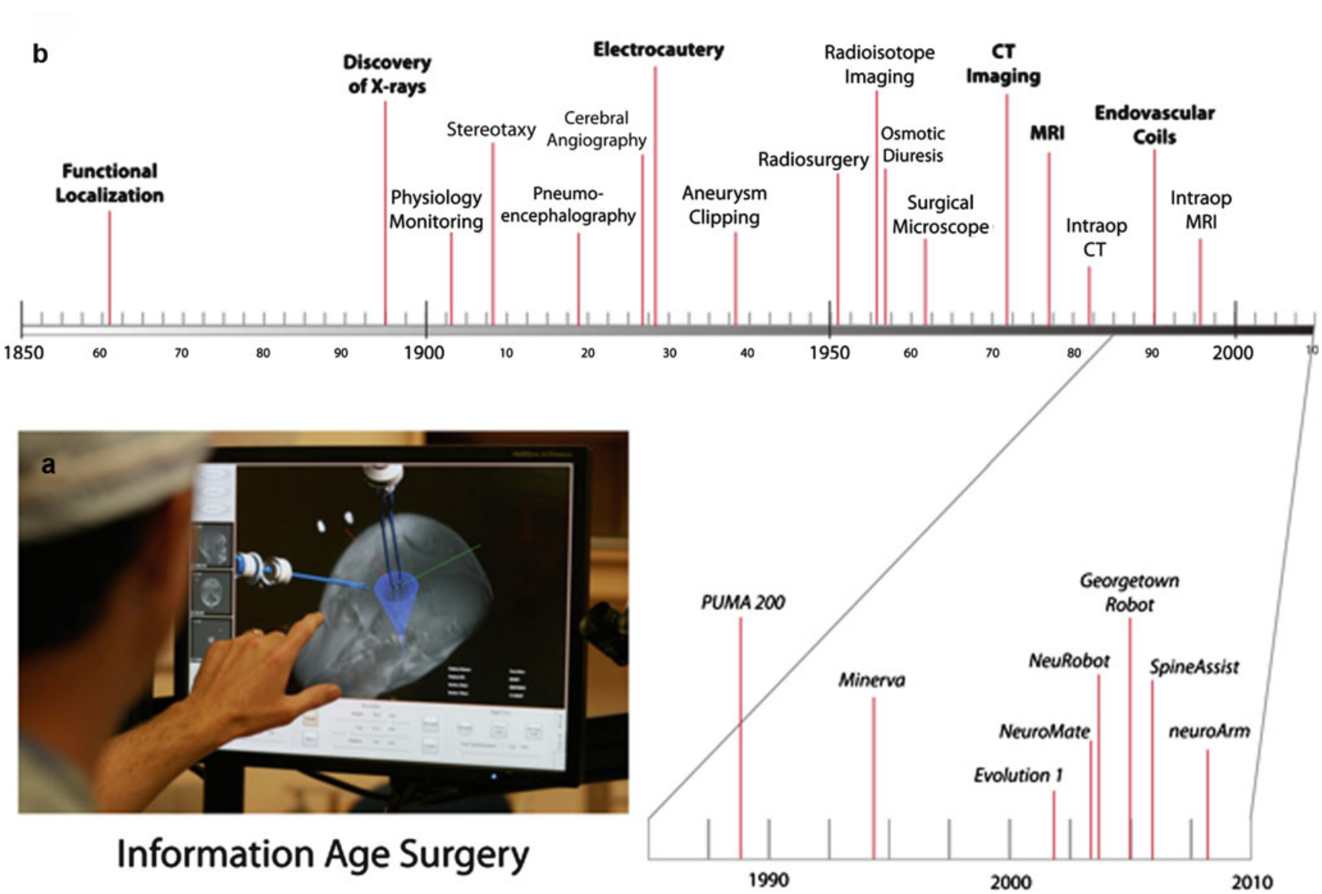

Fig. 46.1 (**a**) Screenshot of the neuroArm human-machine interface showing the integration of 3D magnetic resonance images with surgical planning (*blue cone*) and robotic tools (*blue and off-white*) to target patient pathology. (**b**) Timeline showing the chronological introduction of technologies into clinical neurosurgery. Over the past 20 years, robotic systems have been developed to couple the executive decision-making capacity of the surgeon with the accuracy of imaging technology and the precision of advanced robotics

integrate various imaging technologies into surgical procedure [16–19].

Surgeons were soon provided with exquisite lesion localization before and during each operation. Neurosurgical corridors became smaller, pushing surgeons towards their physical limits of precision, accuracy, and coordination. Investigators from around the world began to integrate robotic technology into the increasingly complex surgical environment. Robotics coupled the executive capacity of the human brain with the increasingly precise and accurate technology of machines. Previously independent technologies are seamlessly integrated at a single-user interface, allowing for synergistic application and multicomponent optimization in any particular clinical exposure. This simplifies access to patient data and facilitates surgery on a smaller scale. The modern neurosurgical paradigm of informatic surgery was thus born [20].

Neurosurgical Robotics

The initial concept of integrating a robotic system into neurosurgery was a daunting proposition. In addition to the technical requirements of the system and its surgical objectives, investigators needed to resolve challenges associated with sterility, patient safety, ethical and regulatory approval, considerable financial cost, integration with imaging technology, and introduction into established surgical procedure and processes. Multidisciplinary cooperation between science, medicine, engineering, and industry was crucial in overcoming the complexity of these challenges. Global awareness and networking allowed incorporation of diverse technologies as they were developed and became available (Fig. 46.1).

Neurosurgical robotics (Table 46.1) began with the introduction of an industrial robot, Programmable Universal Machine for Assembly (PUMA), into the operating theatre in 1985 [21]. In 1987, Benabid et al. coupled the PUMA 200 robot to a Brown-Roberts-Wells (BRW) head frame for frame-based stereotaxy [22]. The robotic arm had six degrees of freedom (DOF), and each joint was equipped with spring-applied, solenoid-release brakes that would immediately stop motion should any system defect arise. Using CT imaging for navigation, the system was able to orient a cannula for needle insertion. The robot was modified to hold a retractor for the resection of multiple pediatric thalamic astrocytomas in 1991 [23]. These developments provided proof of concept of robotic neurosurgery, allowing multidisciplinary

Table 46.1 The evolution of neurosurgical robotics

Year	Project name	DOF	# EE	Navigation	Imaging	Purpose	Documented use	Accomplishments	Limitations
1988	PUMA [21, 23]	6	1	BRW frame	CT	Retractor	Glioma surgery	First neurosurgical robot Demonstration of safety	No FDA approval safety concerns with industrial robot in OR
1994	Minerva [40–42]	5	1	BRW frame	CT	Image guided surgery	Stereotactic biopsy Stereotactic implantation	Mounted inside CT machine	Only five DOF Requires dedicated CT scanner Obstructive within CT gantry
1997	CyberKnife [43]	6	1	Frameless	X-Ray	Radiosurgery	Neurosurgical radiation	Focused radiosurgery FDA approved	Expensive
1999	RAMS [25, 44]	6	1	N/A	N/A	Microsurgery	Rat carotid endarterectomy	Microsurgical ability	No haptic feedback Increased length of procedure
1999	Steady Hand [26]	6	1	N/A	N/A	Microsurgery	Tremor filter and motion stabilizer	Increased surgical precision Haptic feedback	No image guidance No clinical application
2001	Harvard MRI Robot [27, 45]	5	1	Frameless	MRI	Navigation and tool placement	Position needle holder	Non-magnetic actuators	Pointing device only
2002	Evolution 1 [29, 46, 47]	6	1	Frameless	MRI	Endoscopy	Neuroendoscopy Endoscopic ventriculostomy Transphenoidal skull base surgery	Endoscopic application	Narrow working envelop Single arm No haptic feedback
2003	NeuroMate [30, 48–50]	5	1	Frame based or Frameless	CT	Stereotaxy and lesion localization	Stereotaxy Functional neurosurgery Drilling at the skull base	Commercially-available First FDA-approved neurosurg robot Diverse clinical application	No microsurgical ability No tool actuation
2003	NeuRobot [28, 51, 52]	3	3	Frameless	N/A	Microsurgery	Tumor resection	Partial resection of meningioma Telesurgery on rat from 40 km away	Limited to three DOF for each arm Low payload
2005	Georgetown [33, 53]	6	1	N/A	Fluoroscopy	Stereotaxy	Percutaneous facet block	Accuracy comparable to manual technique	Movement occurs in one DOF at a time Requires fluoroscopy suite
2006	Pathfinder [31]	6	1	Frameless	CT	Stereptaxy	Epilepsy surgery	Highly accurate navigation	CT required for feducial placement Surgical ergonomics
2006	SpinAssist [34, 54, 55]	6	1	Frame based	CT	Spinal instrumentation	Guide for tool positioning Guide for screw placement	FDA approval for spinal surgery	Limited range of application
2009	NISS [32]	5	1	CT	CT	CT-guided navigation	Image-guided implantation	In vivo and in vitro surgical implantation	Ionizing radiation
2009	neuroArm [35–39]	7	2	Frameless	MRI	Pre-surgical planning Microsurgery and stereotaxy	Various intracranial pathology Intracranial tumor resection Drainage of cerebral abcess	Microsurgery and stereotaxy MRI-compatible robot and tools Haptic feedback	Expensive

Abbreviations: *DOF* degrees of freedom, *#EE* number of end effectors, *PUMA* Programmable Universal Machine for Assembly, *BRW* Brown-Roberts-Well, *CT* computer tomographic, *FDA* Food and Drug Administration, *OR* Operating Room, *MRI* Magnetic Resonance Imaging, *km* kilometer, *NISS* Neuroscience Institute Surgical System research teams to begin development of robotic systems designed for specific neurosurgical applications.

In 1994, Frankenhauser et al. introduced the Minerva robot [24]. The system was coupled to the same BRW head frame used by Benabid and mounted inside a CT scanner for image-guided biopsy and implantation. Unfortunately, the requirement of a dedicated CT scanner limited applicability of Minerva to the neurosurgical community at large. Two systems, the Robot-Assisted Microsurgical System (RAMS) and Steady-Hand Robotic System, were developed in 1999 to enhance microsurgery [25, 26]. While these projects were shown to improve microsurgical precision and provided haptic feedback, respectively, they have not yet been clinically applied.

By the year 2000, advances in computer technology, the ubiquity of neurological imaging, and increasing adaptation of robotic technology across the manufacturing and aerospace industries provided the potential for development of an image-guided neurosurgical robotic system. The Harvard MRI robot was developed and integrated with intraoperative MR imaging (iMRI) [27]. The robot manipulator was MR compatible and used for intraoperative tool orientation. NeuRobot emerged as a microsurgical robot in 2003 [28]. It was tele-capable and tested in an experimental model with the surgeon located 40 km away from the surgical site.

In addition to developments in microneurosurgery, robotic systems were designed for endoscopic and stereotactic application. The Evolution I robot was developed for endoscopic applications and used in 2002 for the transsphenoidal removal of pituitary adenoma [29]. The CT-based NeuroMate system became the first neurosurgical robot to receive FDA approval for clinical use [30]. The Pathfinder system followed in 2006, with highly accurate CT-guided stereotactic application [31]. Finally, the NISS collaboration was published in 2009 with direct application in CT-guided implantation procedures [32].

Two important robotic systems have been developed for spinal surgery. In 2005, the Georgetown robot was used for fluoroscopy-guided percutaneous facet blocks in cadaveric studies and clinical patients [33]. Accuracy was deemed comparable to manual technique, but movement was only available in one DOF at a time. The SpineAssist robot has been used for tool positioning and pedicle screw placement [34]. It received FDA approval and is commercially available to this day.

neuroArm

Advances in technology provided the opportunity to develop a robotic system capable of both microsurgery and stereotaxy [35]. Furthermore, due to the increasing acceptance of intraoperative MR imaging, it was also desirable to construct a system that could operate within this imaging environment [36]. While this presented significant challenges regarding material selection, technological equipment, and surgical processes, it would resolve the problem of disrupting surgical rhythm for intraoperative image acquisition. In 2002, investigators at the University of Calgary (Calgary, Alberta, Canada), in collaboration with MacDonald, Dettwiler and Associates, began the development of such a robot.

neuroArm: Design and Manufacture

The initial requirements document for neuroArm included the ability to perform both microsurgery and stereotaxy within the bore of a 1.5 T magnet. At the time of preliminary design review, it became evident that stereoscopic vision, a necessary requirement for microsurgery, could not practically be captured within the magnet bore. Furthermore, due to requirements of payload (750 g) and speed (200 mm/s), as well as the size of the existing position encoders, the manipulators needed to be relatively large. Both could not be placed within the 70-cm working aperture of the intraoperative 1.5 T magnet. For these reasons, scope was changed such that image-guided microsurgery would be performed outside of the bore of the magnet and stereotaxy, using a single arm, within the bore of the magnet.

Manipulators

neuroArm consists of two arms called manipulators, each has a total of seven degrees of freedom: six spatial and one degree of tool actuation [37]. Each manipulator was designed to reflect the limbs and joints of a human surgeon: shoulder joint to allow for rotation in both the horizontal and vertical plane, elbow joint to allow for flexion/extension of the arm, and a wrist joint to allow adjustment of rotation and pitch. Tool actuation is accomplished through motion of one tool holder relative to the other. The arms are mounted on a mobile base, which allows height adjustment to accommodate the position of the operating table.

To achieve MR safety, the manipulators were manufactured from titanium, polyetheretherketone (PEEK), and polyoxymethylene (Delrin, Dupont, Wilmington, DE). Motion of the arms is accomplished using ultrasonic piezoelectric actuators (Nanomotion, Yokneam, Israel) that have a 20,000-h lifetime, 1-nm resolution, and inherent braking characteristics if power is lost [36, 37]. Absolute 16-bit sine/cosine encoders provided 0.01° accuracy at each joint and retained positional information when powered off for imaging. Haptic feedback was provided in three translational degrees of freedom from six-axis force/torque sensors (ATI Industrial Automation, Apex, NC) that were specifically

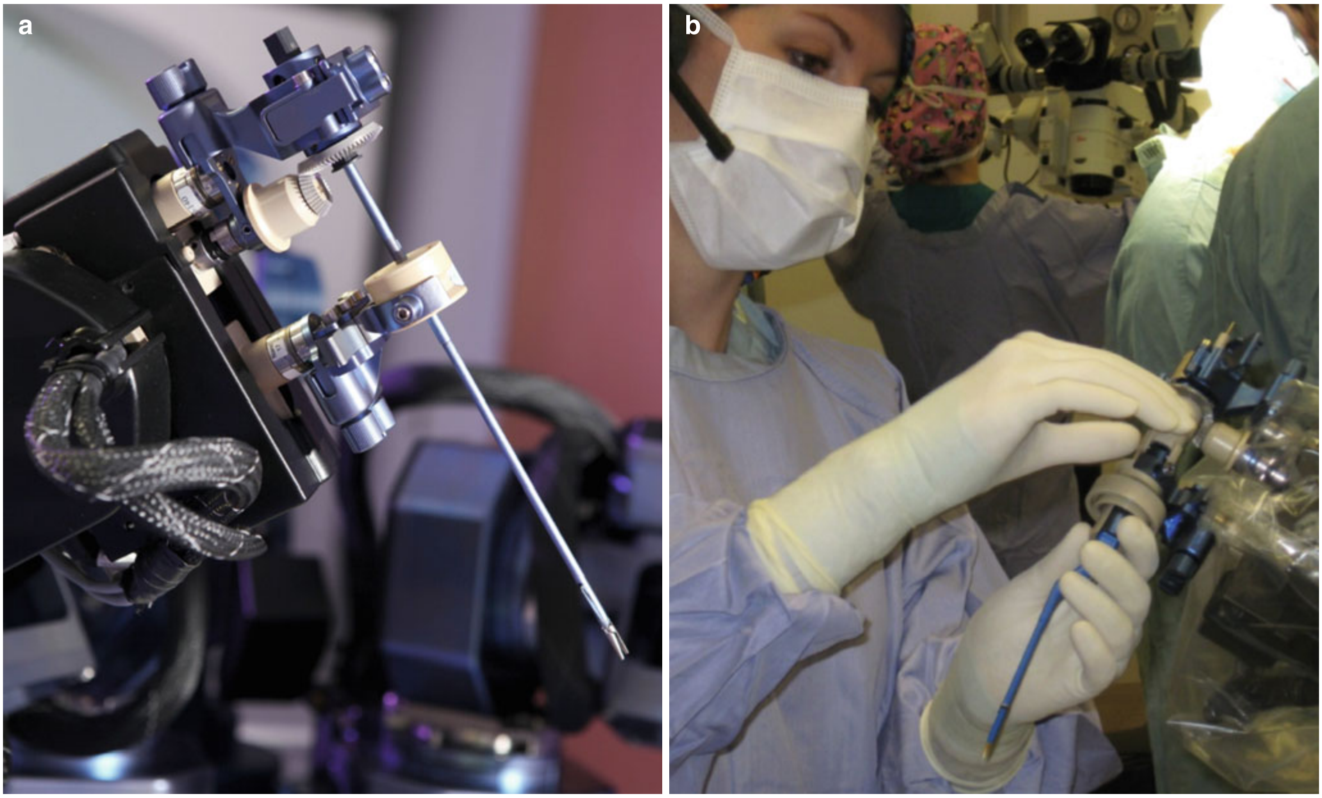

Fig. 46.2 (**a**) The neuroArm end effector uses two standardized connectors (*blue*) to hold a surgical tool. The upper connection includes a gear to control tool roll, while the lower connection moves upward and downward to allow for tool actuation. (**b**) During surgery, the neuroArm manipulators are draped for sterility, while the two standardized tool connectors penetrate the drape. The scrub nurse is able to exchange all the neuroArm tools with the standardized tool connectors

manufactured for neuroArm. The end effectors were designed to hold a variety of tools using a standardized interface that allows for tool roll and tool actuation (Fig. 46.2).

Mobile Base

The manipulators are moved in and out of the operating room on a height-adjustable mobile base. A digitizing arm, mounted on the mobile base, allows registration of the manipulators to the radio frequency (RF) coil. The information, transferred to the computerized human-machine interface, allows 3D MR image display with tool overlay. The field camera, mounted on the mobile base, provides overall visual feed of the surgical field. For stereotactic procedures, the mobile base is used to transport the manipulators to a platform inserted into the MR magnet (Fig. 46.3).

Main System Controller

The main system controller consists of four main software applications, each operating on an individual computer: (1) The command and status display provides the main graphical control interface for the neuroArm end effectors. (2) The MRI display provides 2D and 3D volumetric images of patient pathology with tool overlay. (3) The hand controller interfaces to the left and right human-machine interface hand controllers process kinematic motion at the human-machine interface. (4) The controller interfaces to the manipulator arms and other hardware.

Human-Machine Interface

The human-machine interface recreates the sight, sound, and touch of surgery, while facilitating integration of advanced imaging and surgical planning technologies [38] (Fig. 46.4). Two SONY PMW-10MD Full HD Medical Grade cameras, equipped with 3 one-half-inch (1,920 × 1,080) Exmor™ CMOS sensors, each delivers over two million pixels. Images are then displayed on an LMD-2451MT HD medical monitor that enables surgeons to gain full depth perception and spatial orientation during intricate procedures through clear 3D picture display. Surgeons wear light, comfortable polarized glasses to view the 3D display. These polarized glasses

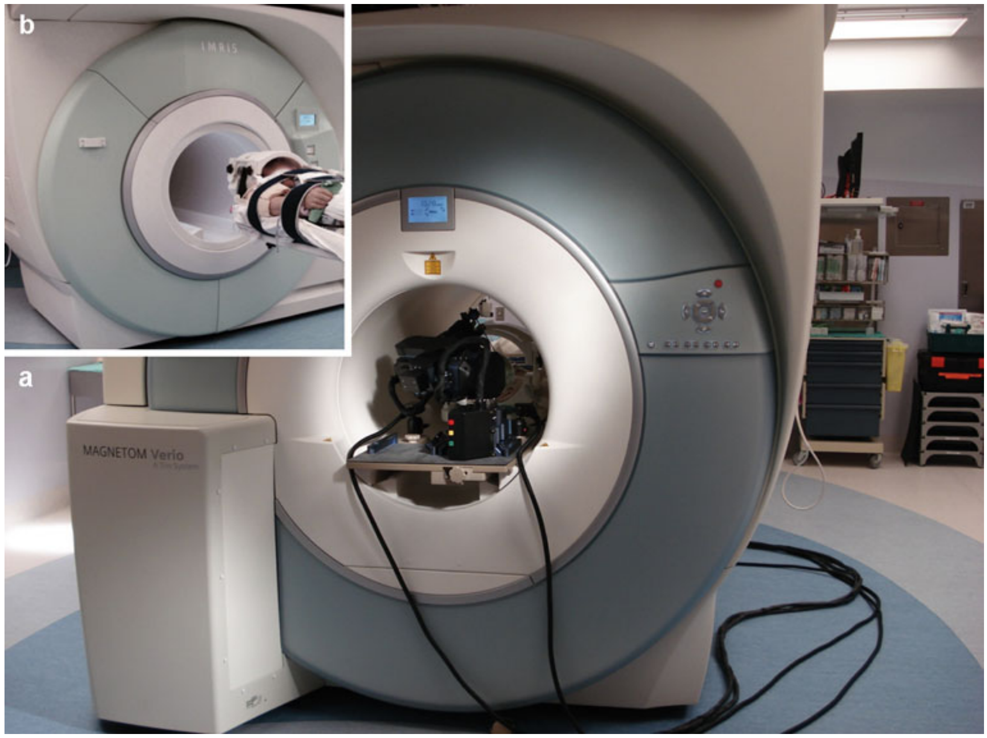

Fig. 46.3 (**a**) During stereotaxy, one neuroArm manipulator is placed on a specialized board within the iMRI magnet bore, opposite to the patient. (**b**) The iMRI machine moves to the operating table, so the patient and neuroArm end effector meet at the magnet isocenter. Stereotaxy near the magnet isocenter allows for simplified registration and optimized image quality throughout the procedure

Fig. 46.4 The neuroArm human-machine interface recreates the sight, sound, and touch of the surgical site for the surgeon. The surgeon is provided with a 3-D stereoscopic view of the surgical corridor. The command status display (right of the stereoscopic display) shows the position of the neuroArm manipulators in relation to the radio frequency coil. The surgeon controls neuroArm using two modified PHANTOM hand controllers, providing seven DOF control with three DOF force feedback. The surgeon communicates with the surgical team using a wireless headset

are almost clear and do not interfere with viewing the other workstation displays.

The MRI display can be manipulated by touch with on-screen controls to view patient-specific MR images in 2D or 3D, with real-time tool overlay. The surgeon is thus able to see the tools as they are manipulated down the surgical corridor and their spatial relationship to the pathology. During stereotaxy, the command status display provides real-time feedback of end-effector orientation relative to the RF coil and magnet bore.

The human-machine interface is height-adjustable, and two modified PHANTOM hand controllers (SensAble Technologies, Inc., Woburn, MA), which provide haptic feedback in three translational degrees of freedom, are mounted at 45° to optimize ergonomics. The surgeon activates each of the manipulators by continuously depressing a

Fig. 46.5 (**a**) For microsurgical procedures, neuroArm is positioned at the operating table in the position of the primary surgeon. The assistant surgeon is able to operate in an ergonomic position relative to neuroArm and the operating microscope. (**b**) The neuroArm bipolar forceps can be used to coagulate as well as remove pathological tissue

corresponding foot pedal. Each pedal acts as an *emergency stop switch*: if disengaged, all motion input to the corresponding manipulator is immediately stopped, bypassing the main system controller. This design is not dependent on the computational capacity of the main system controller, providing the surgeon ultimate control over any adverse motion of the manipulators. Motion scaling and tremor filtration can be applied from the command status display.

As the neuroArm human-machine interface is tele-capable, precise and reliable audio communication with surgical staff is of critical importance (Fig. 46.5). Each member of the surgical team wears a wireless headset with a microphone to maintain smooth surgical rhythm. This alone seems to enhance communication between all members of the surgical team, empowering each member of the surgical team to optimize their role in the procedure

Safety

The creation of a tele-capable human-machine interface provides an ergonomic platform from which the surgeon can interact with complex imaging and sensory datasets. Robotic manipulators then allow the surgeon to operate from the human-machine interface but create unique challenges relative to patient safety.

All motion of the robotic manipulators passes through the main system controller, where input and output from the surgical site are analyzed and interpreted. Computational complexity is increased by redundancy in all manipulator position encoders, force measurements, computer power supplies, and redundant hardware wiring. This introduces the potential for uncontrolled motion of the robotic manipulators at the surgical site should any individual element within the computational processing malfunction. While the software is designed to localize any malfunction in the system, this can take time due to the complex nature of the computation. To overcome this, the *emergency stop switch* was introduced to provide the surgeon with absolute ability to stop robotic motion at any time of the robotic procedure.

In addition, all members of the surgical team are trained on robotic safety, in particular, on the potential for unexpected collision with object or patient. As stereotaxy with neuroArm occurs within the confines of the MR magnet bore, the surgeon is provided with visual feed of the tool by field cameras within the bore. Prior to executing the procedure, the surgeon must perform a verification intraoperative scan containing the tool and destination pathology to assess accuracy of graphical MR tool overlay.

neuroArm: Preclinical Studies

neuroArm and its components arrived and were installed in the intraoperative MR operating theatre at the Seaman Family MR Research Centre (Calgary, Alberta, Canada) in 2008. Regulatory and ethics approval was received in the same year. While such approval is required for clinical application, introduction and acceptance into the international neurosurgical community requires suitable preclinical studies to demonstrate performance and capability of the system within the time-sensitive environment of surgery. A two-stage study was conceived to sequentially test [1] the microsurgical capabilities of neuroArm in a rodent model and [2] the stereotactic capabilities of neuroArm in a cadaveric model [39].

Animal Studies

Animal studies allowed for in situ testing of neuroArm and surgeon acclimatization to the novel neuroArm interface. Compared to conventional neurosurgery, when using neuroArm for microsurgery, surgeons were viewing the surgical site through a 3D interface rather than an operating microscope, manipulating hand controllers rather than the tools directly, requesting tool exchange from the workstation, communicating via wireless headsets, and relying on the assistant surgeon for manipulations requiring additional speed and dexterity at the surgical site. It was found that an experienced surgeon was required as the assistant, in order to maximize the benefits of combining the precision and accuracy of the robot with human speed and dexterity. Surgeons adjusted to these changes within the course of the study, indicating a relatively short learning curve for repetitive procedures.

A Sprague–Dawley rat model was selected to evaluate neuroArm in microsurgery mode. The procedures included bilateral nephrectomy, splenectomy, and submandibular gland excision. Procedures were completed using either neuroArm or conventional hand techniques [39]. Surgeons performed equally well using neuroArm or conventional techniques, showing that neuroArm could be used for microsurgery. The procedure demonstrated that neuroArm included a sufficient haptic interface to allow the surgeon to feel tissue interaction, which is essential for microsurgery. This enabled the progression to clinical studies.

Cadaveric Studies

Following animal studies, the neuroArm navigation system was tested by image-guided implantation of ferrous oxide-coated nanoparticles in a cadaveric model [39]. The heads of the caudate nucleus and globus pallidus were selected as target implantation sites. This was an important preclinical study to evaluate the accuracy of the frameless neuroArm navigation software as compared to an already established navigation system.

Following bilateral frontal craniotomy, the cadaveric specimens were placed in a head clamp. T1-weighted MR images were acquired at 2-mm slice thickness. For neuroArm trials, one neuroArm end effector was placed inside the MR magnet bore and registered to the head clamp and images. The targets were identified, then implantation trajectory was planned using the tool tip extension feature and the Z-lock feature, which restricts end-effector motion to only the direction of the tool axis. These features, coupled with 3D tool overlay at the neuroArm workstation, greatly simplified the implantation procedure. Non-robotic implantation was completed on the contralateral side using a neuronavigation system. The specimens remained in the same head clamp, and the same preoperative T1-weighted MR images were loaded onto the neuronavigation system. For this implantation, the surgeon was presented with sagittal, axial, and coronal images at the tool tip. Following all implantation procedures, the specimens were imaged using the same acquisition sequences to determine the final position of nanoparticles relative to the desired targets. The neuroArm system performed as well as the neuronavigation system.

neuroArm: Clinical Studies

neuroArm represents a novel paradigm for neurosurgery, which created a number of practical considerations for implementation into established neurosurgical procedure. Wireless headsets provided clear communication between the surgical team and the surgeon at the workstation. The scrub nurse was responsible for exchanging the neuroArm tools. Draping and positioning of the robot required careful integration into existing nursing and surgical protocols (Fig. 46.6). Given the complexity of introducing a robot into the operating room, clinical integration of neuroArm was accomplished in a stepwise fashion.

Among the first 22 cases, 10 were meningiomas, 9 gliomas, 2 acoustic schwannomas, and 1 brain abscess. Each of these procedures required general anesthesia and craniotomy. For 4 cases, neuroArm was registered to the intraoperatively acquired surgical planning MR images and used to target the pathology and determine craniotomy placement (Fig. 46.6). In all cases, neuroArm was draped during craniotomy and brought into the surgical field after partial dissection of the pathology. Working at the workstation, the surgeon was able to manipulate tools within the surgical corridors, coagulate vessels to control bleeding, and aspirate (Fig. 46.7). For the brain abscess case, the bipolar forceps, mounted in the right arm, was used to open the capsule and allow drainage of pus.

There was a disruption in the ongoing integration of neuroArm into neurosurgery in 2009, as the 1.5 T iMRI environment with local RF shielding was upgraded to a 3.0 T iMRI suite that included whole-room RF shielding. This upgrade required a 10-month interval, during which the operating room was shut down. The upgrade to whole-room shielding

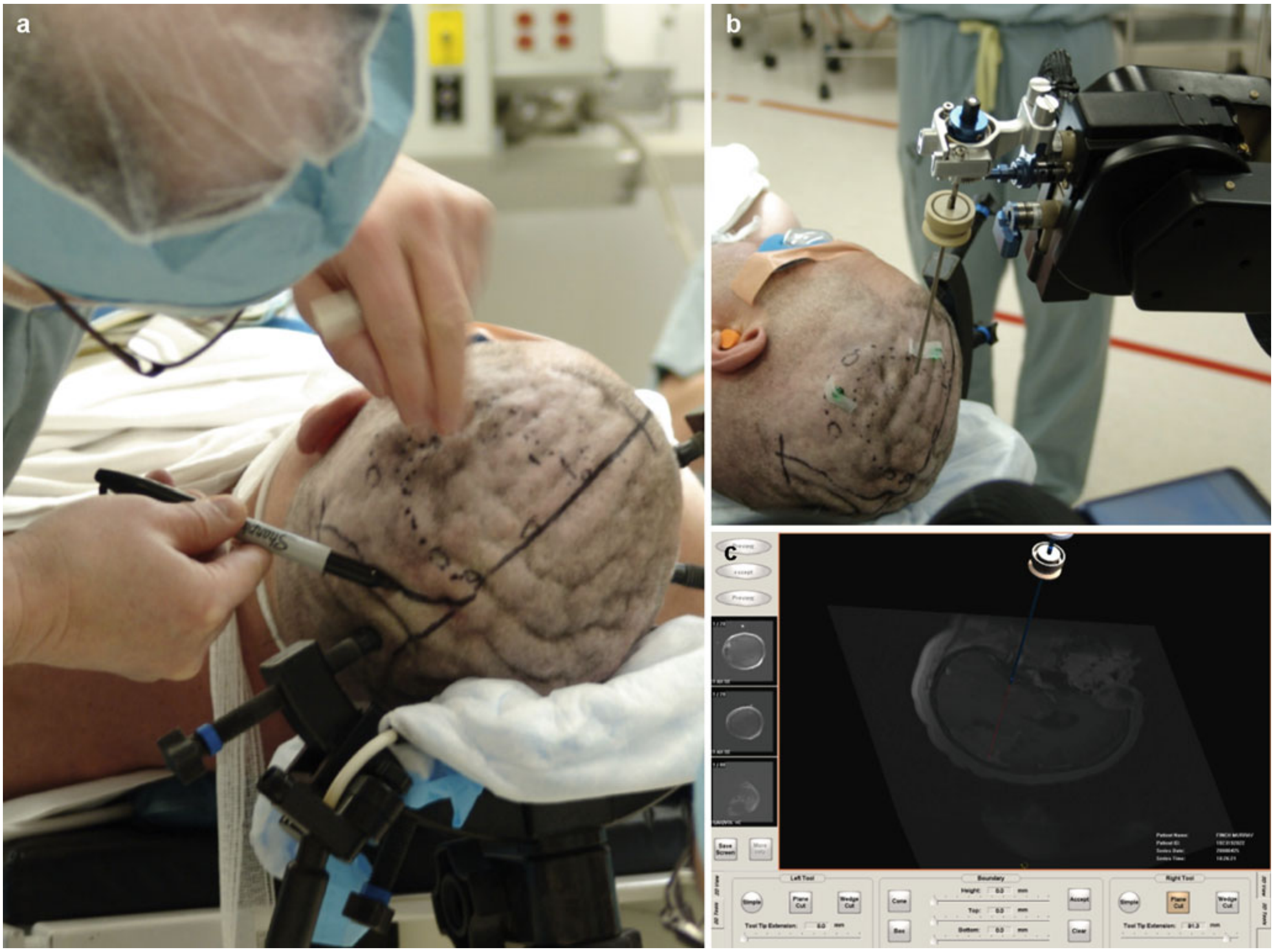

Fig. 46.6 (**a**) Conventional presurgical planning involves marking of the surgical site following anesthetic and fixation with pins in a head clamp. (**b**) Prior to craniotomy, neuroArm navigation software can be used to confirm and refine craniotomy placement based on intracranial pathology. (**c**) Patient-specific MR images are loaded into the MRI display at the neuroArm human-machine interface

allowed dramatic improvements in practical aspects for stereotactic procedures. The manipulator is now able to be attached directly to the magnet bore, rather than being mounted on an extension board from the OR table. Cables are now run through the backside of the magnet, rather than along the OR table, which was previously required to prevent penetration of the RF shielding. Finally, the registration procedure is much simpler as the location of the manipulator is always constant relative to the magnet's isocenter and thus the patient's pathology (Fig. 46.7).

Benefits and Challenges of neuroArm

Several benefits and limitations of using neuroArm were observed. The benefits include:

- Increased motion precision at the distal tool tip from the order of millimeters by hand to the order of micrometers using robotics, aided by the use of tremor filters and motion scaling.
- Increased accuracy of tool tip positioning using absolute positioning sine/cosine encoders.
- Improved neuronavigation interface with 3D tool overlay and Z-lock feature for stereotaxy-biopsy.
- Improved human-machine interface where the surgeon can simultaneously visualize the surgical site, the entire imaging dataset, and the real-time 3D tool overlay.
- Measurement of the forces of tissue dissection is displayed, and the force applied can be limited by filters.

The present challenges of robotic surgery will rapidly change as advances are made in both robotics and human-machine interface technology. Robotic systems of the future will have increased dexterity and the ability to present vital surgical information in a more pragmatic format for the surgeon to utilize. Present challenges of robotic surgery with neuroArm include:

- The dexterity of a human surgeon is approximately 23 DOF controlled by 40 muscles, meaning a tool may be held in a single position with multiple positions of proximal joints in the arms. Due to present computer algorithms, neuroArm dexterity is limited to six DOF: a

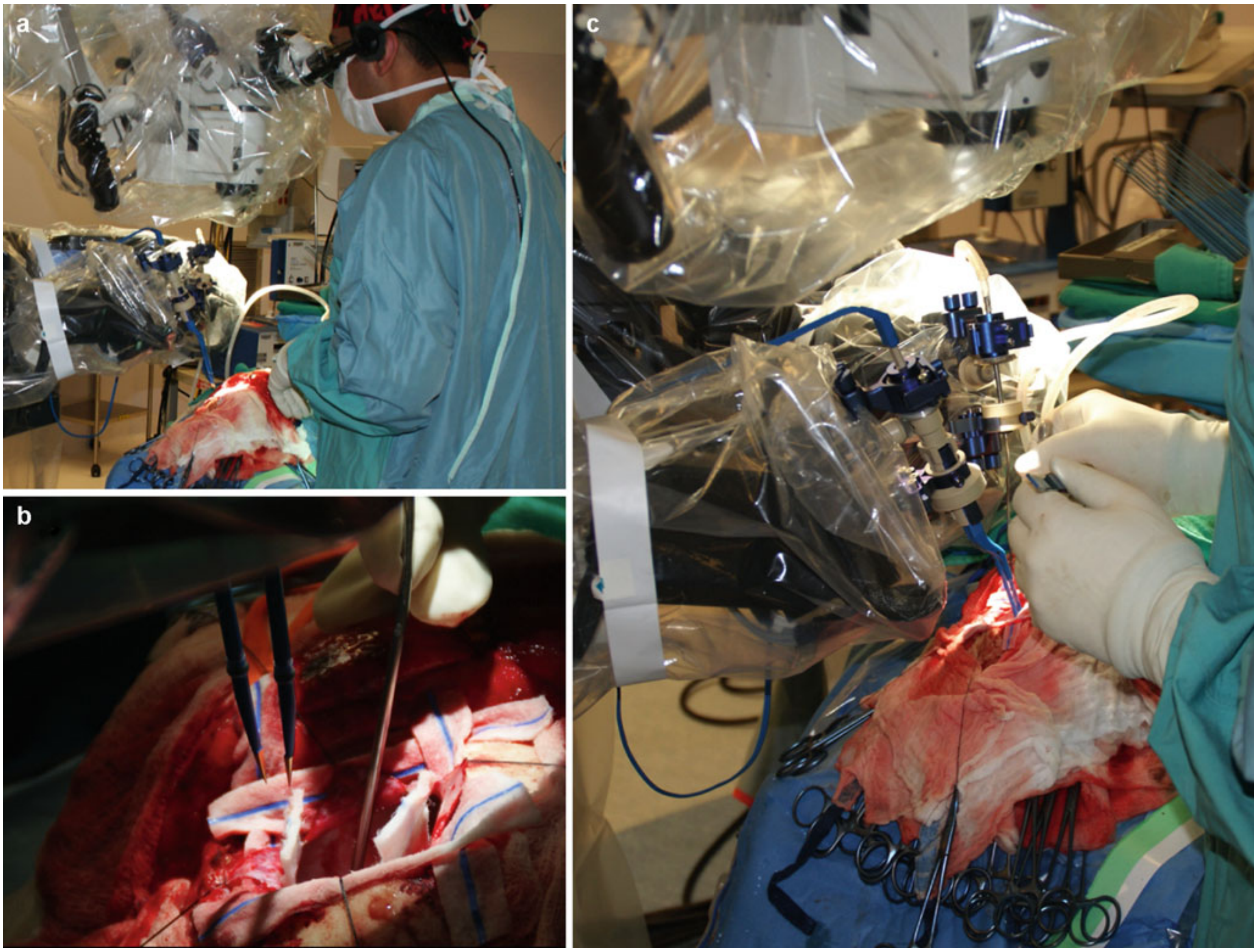

Fig. 46.7 (**a**) Positioning neuroArm into surgical procedure is important so that ergonomics of the surgical assistant and scrub nurse are not compromised. (**b**) At the surgical site, both neuroArm and the assistant surgeon are able to manipulate tools within the surgical corridor. (**c**) Sterile drapes are placed over the neuroArm manipulators, while the tool holders (*blue*) are able to penetrate the sterile drapes and hold the tools

unique combination of proximal joint positions will result in a specific tool position. Increasingly advanced programming algorithms exist in other robotics industries for increased dexterity and are presently being evaluated for future use with neuroArm.

- Perhaps the greatest limitation for widespread application of robotic surgical systems is its decreased ability to provide high- and low-fidelity haptic feedback that is identical or superior to the actual surgical site. The use of neuroArm has allowed us to learn the limitations of our present human-machine haptic interface, which does not yet accurately mimic the force feedback or touch senses of the human surgeon.
- While neuroArm decreases some signal to noise, true MR invisibility has not yet been achieved by neuroArm.
- As computing power increases, it will be possible to increase the sophistication of the neuroArm system, which in turn will support the development of more degrees of freedom and other features.

The future of surgery will involve an increasing number of robotic systems. Perhaps the greatest practical issue preventing the widespread development of robotic systems for surgical applications is the present high cost of medical robotics. However, as robotic technology becomes more universally applied, costs of development and implementation will drop and spark the further development of systems.

Conclusion

The future of neurosurgery lies in the realm of multidisciplinary teamwork. As surgical staff gather increasing clinical experience with neurosurgical robotic systems, robotic technology will continue to be advanced by teams of engineers, scientists, and technologists around the world. Mechanically, advances in MR-compatible robotics will allow miniaturization without sacrifices in surgical performance. This will overcome present spatial limitations and allow movement towards real-time, image-guided microsurgery within the physical constraints of intraoperative imaging devices. The second generation of neuroArm is now in development and will be about 20 % smaller than neuroArm I, allowing both manipulators to enter the imaging space. Additionally, the redesign and selection of new materials will further decrease the mild impact of neuroArm on signal to noise and contrast to noise when acquiring MR images.

Perhaps of more impact to the surgeon will be the rapid upgrades in human-machine interface technology. It is becoming easier to merge pre- and intraoperative images from different modalities in a manner that is surgically relevant and intuitive to manipulate. Improved computer processing will provide relevant real-time data related to anatomy, function, and metabolism. The surgeon will be provided with realistic recreation of touch through ongoing developments in haptic feedback and hand controller design. Measurement of surgical forces and their relationship to tissue deformation will open new areas of research in basic science towards the understanding of tactile perception and its relation to surgical decision-making. As these measurements become more accurate and computer processing progresses, virtual environments will be able to provide realistic training and individualized surgical planning.

Neurosurgical robotics will become the hub of technology in the operating room. It will be possible to interface imaging and surgical management with instantaneous global communication. Advanced tool design will lead to image-guided biopsy and implantation and eventually realization of individualized therapy. Additionally, decreasing component sizes and developments in visual technology will make cell-specific intervention possible.

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References

1. Cushing H, Bovie WT. Electrosurgery as an aid to the removal of intracranial tumors, with a preliminary note on a new surgical-current generator by W.T. Bovie. Surg Gynecol Obstet. 1928; 27:751–85.
2. Kriss TC, Kriss VM. History of the operating microscope: from magnifying glass to microneurosurgery. Neurosurgery. 1998;42(4): 899–907.
3. Yasargil MG. Microsurgery applied to neurosurgery. New York: Academic; 1969.
4. Broca P. Nouvelle observation d'aphe'mie produite par une le´sion de la troisie`me circonvolution frontale. Bulletins de la Socie´te´ d'anatomie 2e serie. 1861;6:398–407.
5. Röntgen WC. Über eine neue Art von Strahlen. Sitzungsberichte der physikalisch-medizinischen Gesellschaft Wiirzburg. 1895; 18(1):137–141.
6. Dandy WE. Roentgenography of the brain after injection of air into the spinal canal. Ann Surg. 1919;70:397.
7. Hounsfield GN. Computerized transverse axial scanning (tomography): part 1. Description of system. Br J Radiol. 1973;46:1016.
8. Lauterbur PC. Progress in n.m.r. zeugmatography imaging. Philos Trans R Soc Lond B Biol Sci. 1980;289(1037):483–7.
9. Mansfield P, Maudsley AA. Medical imaging by NMR. Br J Radiol. 1977;50:188–94.
10. Ogawa S, Tso-Ming L, Nayak AS, et al. Oxygenation-sensitive contrast in magnetic resonance image of rodent brain at high magnetic fields. Magn Reson Med. 1990;14:68–78.
11. Peeling J, Sutherland GR. High-resolution 1H NMR spectroscopy studies of extracts of human cerebral neoplasms. Magn Reson Med. 1992;24:123–36.
12. Lacy AM, Garcia-Valdecasas JC, Delgado S, et al. Laparoscopy-assisted colectomy versus open colectomy for treatment of non-metastatic colon cancer: a randomized trial. Lancet. 2002;359(9325): 2224–9.
13. Liem MS, van der Graaf Y, van Steensel CJ, et al. Comparison of conventional anterior surgery and laparoscopic surgery for inguinal-hernia repair. N Engl J Med. 1997;336(22):1541–7.
14. Kelly PJ, Kall B, Goerss S. Stereotactic CT scanning for the biopsy of intracranial lesions and functional neurosurgery. Appl Neurophysiol. 1983;46:193–9.
15. Kanner AA, Vogelbaum MA, Mayberg MR, et al. Intracranial navigation by using low-field intraoperative magnetic resonance imaging: preliminary experience. J Neurosurg. 2002;97:1115–24.
16. Chandler WF, Knake JE, McGillicuddy JE, et al. Intraoperative use of real-time ultrasonography in neurosurgery. J Neurosurg. 1982; 57(2):157–63.
17. Lunsford LD. A dedicated CT system for the stereotactic operating room. Appl Neurophysiol. 1982;45(4–5):374–8.
18. Black PM, Moriarty T, Alexander 3rd E, et al. Development and implementation of intraoperative magnetic resonance imaging and its neurosurgical applications. Neurosurgery. 1997;41(4):831–5.
19. Sutherland GR, Kaibara T, Louw D, et al. A mobile high-field magnetic resonance system for neurosurgery. J Neurosurg. 1999; 91(5):804–13.
20. Lang MJ, Sutherland GR. Informatic surgery: the union of surgeon and machine. World Neurosurg. 2010;74(1):118–20.
21. Kwoh YS, Hou J, Jonckheere EA, et al. A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery. IEEE Trans Biomed Eng. 1988;35(2):153–60.
22. Benabid AL, Cinquin P, Lavaile S, et al. Computer-driven robot for stereotactic surgery connected to CT scan and magnetic resonance imaging: technological design and preliminary results. Appl Neurophysiol. 1987;50(1–6):153–4.
23. Drake JM, Joy M, Goldenberg A, et al. Computer- and robot-assisted resection of thalamic astrocytomas in children. Neurosurgery. 1991;29(1):27–33.
24. Fankhauser H, Glauser D, Flury P, et al. Robot for CT-guided stereotactic neurosurgery. Stereotact Funct Neurosurg. 1994;63(1–4): 93–8.
25. Le Roux PD, Das H, Esquenazi S, et al. Robot-assisted microsurgery: a feasibility study in the rat. Neurosurgery. 2001;48(3):584–9.
26. Taylor R, Jensen P, Whitcomb L, et al. A steady-hand robotic system for microsurgical augmentation. Int J Robot Res. 1999;18(12): 1201–10.
27. Chinzei K, Miller K. Towards MRI guided surgical manipulator. Med Sci Monit. 2001;7(1):153–63.

28. Hongo K, Kobayashi S, Kakizawa Y, et al. NeuRobot: telecontrolled micromanipulator system for minimally invasive microneurosurgery-preliminary results. Neurosurgery. 2002;51(4):985–8.
29. Zimmermann M, Krishnan R, Raabe A, et al. Robot-assisted navigated endoscopic ventriculostomy: implementation of a new technology and first clinical results. Acta Neurochir (Wien). 2004;146(7):697–704.
30. Varma TR, Eldridge PR, Forster A, et al. Use of the NeuroMate stereotactic robot in frameless mode for movement disorder surgery. Stereotact Funct Neurosurg. 2003;80(1–4):132–5.
31. Eljamel MS. Robotic application in epilepsy surgery. Int J Med Robot. 2006;2:233–7.
32. Chan F, Kassim I, Lo C, et al. Image-guided robotic neurosurgery – an in vitro and in vivo point accuracy evaluation experimental study. Surg Neurol. 2009;71(6):640–7.
33. Cleary K, Watson V, Lindisch D, et al. Precision placement of instruments for minimally invasive procedures using a "needle driver" robot. Int J Med Robot. 2005;1(2):40–7.
34. Lieberman IH, Togawa D, Kayanja MM, et al. Bone-mounted miniature robotic guidance for pedicle screw and translaminar facet screw placement: part I – technical development and a test case result. Neurosurgery. 2006;59(3):641–50.
35. Louw DF, Fielding T, McBeth PB, et al. Surgical robotics: a review and neurosurgical prototype development. Neurosurgery. 2004; 54(3):525–36; discussion 536–7.
36. Sutherland GR, Latour I, Greer AD. Integrating an image-guided robot with intraoperative MRI: a review of the design and construction of neuroArm. IEEE Eng Med Biol Mag. 2008;27(3):59–65.
37. Sutherland GR, Latour I, Greer AD, et al. An image-guided magnetic resonance-compatible surgical robot. Neurosurgery. 2008;62(2):286–92; discussion 292–3.
38. Greer AD, Newhook P, Sutherland GR. Human-machine interface for robotic surgery and stereotaxy. IEEE/ASME Trans Mech. 2008;13(3):355–61.
39. Pandya S, Motkoski JW, Serrano-Almeida C, et al. Advancing neurosurgery with image-guided robotics. J Neurosurg. 2009;111(6): 1141–9.
40. Glauser D, Fankhauser H, Epitaux M, et al. Neurosurgical robot Minerva: first results and current developments. J Image Guid Surg. 1995;1(5):266–72.
41. Hefti J-L, Epitaux M, Glauser D, et al. Robotic three-dimensional positioning of a stimulation electrode in the brain. Comput Aided Surg. 1998;3:1–10.
42. Fankhauser H, Glauser D, Flury P, et al. Robot for CT-guided stereotactic neurosurgery. Stereotact Funct Neurosurg. 1994;63:93–98.
43. Adler JR Jr., Chang SD, Murphy MJ, et al. The Cyberknife: A frameless robotic system for radiosurgery. Stereotact Funct Neurosurg. 1997;69:124–8.
44. Das H, Zak H, Johnson J, et al. Evaluation of a telerobotic system to assist surgeons in microsurgery. Comput Aided Surg. 1999;4(1):15–25.
45. Chinzei K, Warfield SK, Hata N, et al. Planning, simulation and assistance with intraoperative MRI. Minim Invasive Ther Allied Technol. 2003;12(1-2):59–64.
46. Zimmermann M, Krishnan R, Raabe A, Seifert V. Robot-assisted navigated neuroendoscopy. Neurosurgery. 2002;51(6):1446–52.
47. Nimsky Ch, Rachinger J, Iro H, et al. Adaptation of a hexapod-based robotic system for extended endoscope-assisted transsphenoidal skull base surgery. Minim Invasive Neurosurg. 2004;47(1):41–6.
48. Li QH, Zamorano L, Pandya A, et al. The application accuracy of the NeuroMate robot-A quantitative comparison with frameless and frame-based surgical localization systems. Comput Aided Surg. 2002;7(2):90–8.
49. Varma TR, Eldridge P. Use of the NeuroMate stereotactic robot in a frameless mode for functional neurosurgery. Int J Med Robot Comp. 2006;2(2):107–13.
50. Xia T, Baird C, Jallo G, et al. An integrated system for planning, navigation and robotic assistance for skull base surgery. Int J Med Robot Comp. 2008;4(4):321–30.
51. Goto T, Hongo K, Kakizawa Y, et al. Clinical application of robotic telemanipulation system in neurosurgery: case report. J Neurosurg. 2003;99(6):1082–4.
52. Hongo K, Goto T, Miyahara T, et al. Telecontrolled micromanipulator system (NeuRobot) for minimally invasive neurosurgery. Acta Neurochirurgica Supplement. 2006;98:63.
53. Cleary K, Stoianovici D, Patriciu A, et al. Robotically assisted nerve and facet blocks: a cadaveric study. Acad Radiol. 2002;9(7):821–5.
54. Sukovich W, Brink-Danan S, Hardenbrook M. Miniature robotic guidance for pedicle screw placement in posterior spinal fusion: early clinical experience with the SpineAssist®. Int J Med Robot Comp. 2006;2(2):114–22.
55. Barzilay Y, Liebergall M, Fridlander A, et al. Miniature robotic guidance for spine surgery—introduction of a novel system and analysis of challenges encountered during the clinical development phase at two spine centres. Int J Med Robot Comp. 2006;2(2):146–53.