Merging machines with microsurgery: clinical experience with neuroArm

Clinical article

GARNETTE R. SUTHERLAND, M.D., SANJU LAMA, M.D., LIU SHI GAN, PH.D., STEFAN WOLFSBERGER, M.D., AND KOUROSH ZAREINIA, PH.D.

Department of Clinical Neurosciences and the Hotchkiss Brain Institute, University of Calgary, Alberta, Canada

Object. It has been over a decade since the introduction of the da Vinci Surgical System into surgery. Since then, technology has been advancing at an exponential rate, and newer surgical robots are becoming increasingly sophisticated, which could greatly impact the performance of surgery. NeuroArm is one such robotic system.

Methods. Clinical integration of neuroArm, an MR-compatible image-guided robot, into surgical procedure has been developed over a prospective series of 35 cases with varying pathology.

Results. Only 1 adverse event was encountered in the first 35 neuroArm cases, with no patient injury. The adverse event was uncontrolled motion of the left neuroArm manipulator, which was corrected through a rigorous safety review procedure. Surgeons used a graded approach to introducing neuroArm into surgery, with routine dissection of the tumor-brain interface occurring over the last 15 cases. The use of neuroArm for routine dissection shows that robotic technology can be successfully integrated into microsurgery. Karnofsky performance status scores were significantly improved postoperatively and at 12-week follow-up.

Conclusions. Surgical robots have the potential to improve surgical precision and accuracy through motion scaling and tremor filters, although human surgeons currently possess superior speed and dexterity. Additionally, neuroArm’s workstation has positive implications for technology management and surgical education. NeuroArm is a step toward a future in which a variety of machines are merged with medicine.

(https://thejns.org/doi/abs/10.3171/2012.11.JNS12877)

Key Words • brain tumor • intraoperative magnetic resonance imaging • microsurgery • surgical robotics • technology • surgical technique

Technological developments enable neurosurgeons to address the broad spectrum of disorders that affect the central and peripheral nervous systems with increasing effectiveness. These disorders impact patients’ quality of life and are a considerable social and financial burden.7 The interconnectivity of the brain requires that neurosurgeons operate with precise localization to protect the brain’s functionality.3,11,18 Surgical robotics represents a leap forward in precision and accuracy, which together with advances in imaging technology, has the potential to shift the paradigm of surgery toward the cellular level.20

NeuroArm is a cutting-edge image-guided teleoperated robotic system developed by researchers at the University of Calgary in collaboration with MacDonald, Dettwiler and Associates Ltd.6,13,19 Conventionally, surgeons tend to leave the surgical site to view imaging data and cannot interact with the images without breaking sterility. NeuroArm provides the operating surgeon with access to sophisticated imaging data without interrupting surgical procedure. The system consists of 2 MR-compatible robotic arms, called manipulators, and a workstation with a sensory immersive human-machine interface connected via a main system controller. Each neuroArm manipulator has 7 degrees of freedom, and each joint has 2 absolute sine/cosine encoders, while an optical encoder provides tool roll.19 The workstation provides access to MR images and real-time high-definition 3D images of the surgical site. Modified Phantom premium hand controllers (Sensible Technologies Inc./Geomagic) allow the manipulators to emulate the surgeon’s hand movements. NeuroArm is capable of maneuvering a wide array of surgical instruments, including both specially designed microsurgical instruments and existing tools.
Following preclinical testing, neuroArm was introduced to neurosurgery in a graded fashion. Although neuroArm’s first clinical cases were performed in 2008, its use was put on hiatus in June 2008 while the iMRI OR was upgraded from a 1.5-T iMRI system with localized shielding to accommodate a 3-T iMRI system with whole-room radiofrequency shielding. This process required the redevelopment of portions of neuroArm for integration into the 3-T system. After the OR upgrades and a safety review were complete, cases resumed in October 2010.

Methods

This is a prospective series of the first 35 neuroArm cases. All but one of the patients presented to the outpatient clinic of the senior author (G.R.S.). One patient with a brain abscess was admitted to the hospital from the emergency room. Each patient provided informed consent, and procedures took place at the Foothills Medical Centre, Calgary, Alberta, Canada. All data are presented as a mean ± SEM. Comparisons between pre- and postoperative Karnofsky scores were performed using the Student t-test. Results are reported with a significance of p < 0.01. For all patients, OR data were acquired including total OR time, OR preparation time that included surgical planning iMRI, incision-to-closure time, and neuroArm use time. In addition, length of hospital stay and preoperative, postoperative, and 12-week follow-up KPS scores were recorded. Adverse events and surgical complications were also recorded. All procedures were performed in compliance with the University of Calgary Conjoint Health Research Ethics Board of the Faculties of Medicine, Nursing, and Kinesiology and with Health Canada guidelines. Use of neuroArm was instituted in a graded fashion to account for the multiple variables that an image-guided robotic system introduces to surgery.

Intraoperative images were acquired using a prototype 1.5-T iMRI system for the first 5 cases and the 3-T iMRI system for the remaining 30 cases. Imaging sequences included T1-weighted MRI, FLAIR, MR angiography, MR venography, diffusion tensor imaging, and T1-weighted imaging with gadolinium where indicated. Surgical exposure, including craniotomy and opening of the dura, was performed using conventional technique. During the opening, the robotic arms were draped, and sterilized components for holding and actuating surgical tools, including bipolar forceps, tissue forceps, a needle driver, tissue dissectors, suction, and microscissors, were placed into the right and left manipulators. The surgical microscope, modified with 2 high-definition cameras that provide the workstation’s stereoscopic vision of the surgical site, was draped. The operating staff was provided with communication headsets to allow communication with the surgeon located at the neuroArm workstation outside of the OR. NeuroArm was positioned as the primary surgeon for microsurgical dissection. The neurosurgical resident assumed the role of surgical assistant for all cases. In some cases neuroArm was registered to the intraoperatively acquired images following image acquisition but prior to draping.

Results

The neuroArm system overview is presented in Figs. 1 and 2. Figure 1 displays the 7 degrees of freedom and internal components of a neuroArm manipulator. Figure 2 shows the relationship of the workstation to all the other elements in the OR. The first neuroArm cases involved 35 patients (17 male and 18 female) with an average age of 48 ± 3 years (range 18–74 years). Patient characteristics are presented with KPS scores in Table 1. The KPS scores acquired following surgery and at 12 weeks were significantly better than preoperative scores (p < 0.01).

The mean total OR time was 7 hours, of which almost 2 hours was preparation time, which included the surgical planning iMRI study and surgical navigation setup (Table 2). Surgical planning and quality assurance iMRI studies added approximately 60 minutes to the total OR time. The mean incision-to-closure time was 4.5 hours. NeuroArm was used for an average of 60 minutes per operation. The process of plugging the manipulators into the neuroArm system and draping each manipulator was straightforward and required less than 10 minutes. Sterile tool holders and tool roll gears were inserted through the sterile drape, maintaining sterility (Fig. 3). In the 35 cases there has not been a single infection. Only 1 patient experienced a surgical complication, transient facial nerve palsy, and there was 1 adverse event involving unintended manipulator motion. These 35 elective-surgery patients spent on average 3 days in the hospital.

NeuroArm works in tandem with a surgical assistant. An experienced surgical assistant provides the dexterity that the robot currently lacks. The operating surgeon communicates with the surgical assistant via headset, so that the movements of neuroArm are coordinated with the actions of the surgical assistant (Fig. 4). The presence of the assistant compensates for the surgical robot’s speed, which is kept low to ensure safety (Video 1).

**Video 1.** Clip showing removal of a WHO Grade II astrocytoma. The right manipulator is holding the bipolar forceps and the left manipulator a tissue forceps, initially retracting brain and then tumor. NeuroArm is used to coagulate and divide the tumor-brain interface, and also to obtain hemostasis in the resection cavity. Modified from www.neuroArm.org with permission. Click here to view with Media Player. Click here to view with Quicktime.

NeuroArm is able to hold tools in a steady position where a human surgeon might experience fatigue and is able to access a narrow surgical corridor while avoiding brain retractors (Video 2).

**Video 2.** Clip showing the neuroArm working within a narrow subtemporal surgical corridor for excision of a disseminated medulloblastoma. The right manipulator is used to coagulate the tumor and the left to remove the tumor with suction. The assistant surgeon holds a suction device. Click here to view with Media Player. Click here to view with Quicktime.

The learning curve for neuroArm is relatively steep, and so routine dissection of the tumor-brain interface has only occurred over the last 15 cases (Fig. 5). The use of the robot increased with each subsequent case as the surgeon became more comfortable with the machine and learned how to adjust for variations in pathology.

NeuroArm was positioned at the surgical site in a...
manner that did not affect nursing and anesthesia management. The surgical assistant was positioned directly opposite the robot as 2 high-definition cameras occupied the side ports on the viewing head of the microscope (Fig. 4). Additionally, the symmetry produced by the position of the surgical assistant facilitated the cooperation between the surgeon and the assistant. It was only necessary in 1 case (3%) to convert from use of the robot to conventional microsurgical technique. Due to an intact superior sagittal sinus, the patient had a right-side craniotomy for a posterior parafalcine meningioma that extended to the contralateral side. It was problematic for both the assistant and the manipulators to access the restricted surgical corridor via the shallow angle needed to resect the tumor on the left side. Accordingly, the use of the robot was abandoned, and surgery proceeded with conventional technique.

The only adverse event with the potential for patient injury occurred in Case 5. This event involved unintended motion. The patient was not injured by that motion, though he experienced a facial nerve palsy that was presumed to be due to manipulation of the facial nerve or the irritating effect of dermoid cyst contents. A translabyrinthine exposure was performed for excision of a recurrent prepontine dermoid cyst. Using neuroArm, the tumor capsule was coagulated and the lesion entered. The cyst contents were aspirated with the left manipulator suction tool. During this stage, the left manipulator made an unintended motion, moving to the left when commanded to move to the right. As a result, the suction tool broke when it hit a retractor. The remainder of the procedure was accomplished using only the right manipulator with the surgical assistant completing the aspiration of dermoid cyst contents. This unexpected movement triggered a safety review.

The safety review determined that the uncontrolled movement was caused by an encoder failure of a joint angle sensor, enabling the manipulator to move 2.4 cm in an unintended direction. The solution was the implementation of an emergency stop switch, operated by the surgeon, connecting the workstation directly to the manipulator arms, bypassing the main system controller. The review also reassessed the potential hazards of introducing robotics into the OR (Fig. 6). Safety requirements were obtained from the Canadian Medical Devices Regulations and 21 CFR Parts 800–1299 (US Food and Drug Administration), and guidance documents from the Global Harmonization Task Force.

Technological advances incorporated into neuroArm further facilitate the surgeon’s interaction with the robotic system. In 2011, the vision system changed from a binocular stereoscopic display to a 3D monitor display, which enables the surgeon to view both the surgical site and the hand controllers simultaneously. The upgraded vision system has a 24-in widescreen 3D stereoscopic monitor with 1920 × 1200 resolution, 60 Hz refresh rate, and 3D micropolarizer filter (Sony). The primary neurosurgeon wears passive 3D glasses to visualize the display. The 3D monitor allows residents and observers wearing 3D glasses a stereoscopic view of the operating field, which was limited to the primary neurosurgeon in the case of the binocular display.
Fig. 2. An overview of the neuroArm system.

TABLE 1: Summary of patient characteristics including preoperative, postoperative, and 12-week follow-up KPS scores

<table>
<thead>
<tr>
<th>Diagnostic Group</th>
<th>No. of Pts &amp; Sex</th>
<th>Age (yrs)</th>
<th>Preop KPS</th>
<th>Postop KPS</th>
<th>12-Wk KPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>high-grade glioma</td>
<td>3 M</td>
<td>45 ± 4</td>
<td>87 ± 3</td>
<td>87 ± 3</td>
<td>87 ± 3</td>
</tr>
<tr>
<td>low-grade glioma</td>
<td>4 F, 4 M</td>
<td>46 ± 5</td>
<td>91 ± 1</td>
<td>95 ± 2</td>
<td>99 ± 1</td>
</tr>
<tr>
<td>meningioma</td>
<td>11 F, 5 M</td>
<td>48 ± 4</td>
<td>86 ± 2</td>
<td>91 ± 2</td>
<td>95 ± 2</td>
</tr>
<tr>
<td>schwannoma</td>
<td>2 F</td>
<td>60 ± 10</td>
<td>90 ± 0</td>
<td>90 ± 0</td>
<td>90 ± 0</td>
</tr>
<tr>
<td>dermoid cyst</td>
<td>1 M</td>
<td>55</td>
<td>90</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td>metastatic carcinoma</td>
<td>1 M</td>
<td>61</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>abscess</td>
<td>1 M</td>
<td>43</td>
<td>90</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>cavernous angioma</td>
<td>1 M</td>
<td>72</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>radiation necrosis</td>
<td>1 F</td>
<td>62</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>medulloblastoma</td>
<td>1 M</td>
<td>30</td>
<td>90</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>all pts</td>
<td>18 F, 17 M</td>
<td>48 ± 3</td>
<td>87 ± 2</td>
<td>89 ± 2†</td>
<td>93 ± 2†</td>
</tr>
</tbody>
</table>

* Results are presented as mean ± SEM or as a single value for categories with only 1 case. Abbreviation: Pts = patients.
† p < 0.01 compared to preoperative score.
Merging machines with microsurgery

Discussion

The results show that an image-guided robotics system can be successfully integrated into neurosurgery. These 35 cases, although they do represent the spectrum of intracranial neurosurgery, are relatively selected. Other than cavernous angioma, vascular pathologies such as aneurysms (as a clip applier has yet to be developed) or arteriovenous malformations (due to the surgical challenge) were purposefully excluded. Despite the integration of a complex new technology into the OR, only 2 of these surgical cases exceeded the allocated OR time: Case 2, a large posterior parafalx meningioma, and Case 4, a moderate-sized subfrontal olfactory groove meningioma. The robot use durations reflect the purposefully graded introduction of the robot into surgery. The KPS scores showed significant improvement, and only 1 patient suffered transient facial nerve palsy, and this was presumed to be related to the patient’s disease rather than the use of the robot. The short hospital stay reflects the elective nature of the procedures rather than any benefit attributable to neuroArm.

As previously reported by our group, the use of iMRI lengthens surgery. This is due, in part, to the changes in anesthetizing, positioning, and monitoring the patient and the necessary safety protocol for use of the magnet during surgery. In most cases, 3 or 4 imaging sequences are acquired for surgical planning iMRI and 1 or 2 imaging sequences for quality assurance iMRI, which accounts for the difference in time between these 2 iMRI acquisitions. In most cases, intradissection imaging was not used. In order to leave more time to focus on the integration of the robot into surgery, cases were selected that were relatively unlikely to benefit from intradissection imaging. The incision-to-closure times reported here are comparable to those in similar cases performed in conventional neurosurgical ORs by the same surgeon. For example, the incision-to-closure time for glioma resection is 240 minutes in the conventional OR and for acoustic schwannoma resection, it is 360 minutes.

In one case, use of neuroArm was halted in favor of conventional microsurgical technique because it was difficult for both the assistant and the manipulators to simultaneously access a restricted surgical corridor. However, this problem also exists in conventional surgery, where the assistant surgeon might not be able to operate alongside the surgeon in certain cases in which positioning cannot accommodate access for more than one surgeon. With each generation of surgical machines there is a decrease in the size of components, which should result in this particular challenge of surgical integration disappearing within the foreseeable future. In no other case did neuroArm negatively affect established neurosurgical, nursing, and anesthetic procedures.

Among the 35 cases, a single adverse event occurred, uncontrolled movement, which did not cause patient injury but did initiate a safety review conducted by MacDon-

---

**TABLE 2: Results with respect to time use and length of hospital stay**

<table>
<thead>
<tr>
<th>Diagnostic Category</th>
<th>Total OR Time (min)</th>
<th>OR Prep (min)</th>
<th>Skin to Skin (min)</th>
<th>SP iMRI (min)</th>
<th>ID iMRI (min)</th>
<th>QA iMRI (min)</th>
<th>neuroArm Use (min)</th>
<th>LOS (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>high-grade glioma</td>
<td>420 ± 10</td>
<td>130 ± 10</td>
<td>260 ± 20</td>
<td>50 ± 20</td>
<td>25</td>
<td>30</td>
<td>60 ± 30</td>
<td>6 ± 3</td>
</tr>
<tr>
<td>low-grade glioma</td>
<td>410 ± 30</td>
<td>114 ± 8</td>
<td>260 ± 20</td>
<td>29 ± 3</td>
<td>25 ± 2</td>
<td>60 ± 14</td>
<td>2.3 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>meningioma</td>
<td>440 ± 30</td>
<td>115 ± 7</td>
<td>290 ± 30</td>
<td>33 ± 3</td>
<td>21 ± 2</td>
<td>59 ± 9</td>
<td>2.9 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>schwannoma</td>
<td>505 ± 1</td>
<td>119 ± 2</td>
<td>340 ± 40</td>
<td>20 ± 0</td>
<td>25 ± 0</td>
<td>30 ± 0</td>
<td>6 ± 3</td>
<td></td>
</tr>
<tr>
<td>dermoid cyst</td>
<td>460</td>
<td>110</td>
<td>340</td>
<td>40</td>
<td></td>
<td>60</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>metastatic carcinoma</td>
<td>325</td>
<td>115</td>
<td>129</td>
<td>30</td>
<td></td>
<td>20</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>abscess</td>
<td>353</td>
<td>72</td>
<td>123</td>
<td>17</td>
<td></td>
<td>40</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>cavernous angioma</td>
<td>340</td>
<td>116</td>
<td>189</td>
<td>30</td>
<td>30</td>
<td>60</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>radiation necrosis</td>
<td>272</td>
<td>92</td>
<td>148</td>
<td>30</td>
<td>15</td>
<td>90</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>medulloblastoma</td>
<td>465</td>
<td>108</td>
<td>331</td>
<td>30</td>
<td>15</td>
<td>75</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>all cases</td>
<td>420 ± 20</td>
<td>114 ± 4</td>
<td>270 ± 20</td>
<td>33 ± 2</td>
<td>25</td>
<td>23 ± 1</td>
<td>58 ± 6</td>
<td></td>
</tr>
</tbody>
</table>

* Values are presented as mean ± SEM or as a single value for categories with only 1 case. Abbreviations: ID = intradissection; LOS = length of hospital stay; Prep = preparation; QA = quality assurance; SP = surgical planning.

---

**Fig. 3.** Photograph of the neuroArm showing the sterile drapes covering the neuroArm manipulators. The right manipulator displays the tool holder assembly and attached bipolar forceps. The left manipulator shows penetration of the sterile drape by the upper and lower tool holders and tool roll gear.
ald, Dettwiler and Associates. Their engineering safety review consists of a comprehensive analysis of the entire robotic system. This safety review is conducted by a safety department that is within MacDonald, Dettwiler and Associates but external to the neuroArm program and occurs automatically if the robot’s digital records indicate a problem. Robot integration stops until the review is completed and the agency presents its results to all physicians and engineers involved with the project. This model of an external safety regulating body comes from aerospace but should be considered for all medical robotics, as it builds in a high level of safety separate from the interests of the investigators and industrial partners constructing the robot.

Uncontrolled motion remains one of the most serious problems to address in surgical robots because of the potential risk of patient injury. One way to mitigate uncontrolled motion is to slow down the robot's movement so that any uncontrolled motion can be halted before the robot has moved any significant distance. Another method of reducing uncontrolled motion is to incorporate human correction into the system. One of neuroArm’s upgrades installed a foot-operated emergency stop that turns off the robot without interfacing through the computer, which bypasses the processing time between identifying a problem and halting motion. The emergency stop functions as an activation switch: the robot can only move if the surgeon’s foot holds down the switch, and movement ceases when the surgeon releases the switch. The previous emergency stop was a thumb switch that did not halt the robot instantaneously because the commands were routed through the computer. The surgeons operating neuroArm found that the footswitch design was more intuitive to operate than the thumb switch. There are additional emergency stop buttons on the mobile base and at the workstation so that anyone can halt the robot; however, there has been no need to use these switches to date. Uncontrolled motion has not been observed in the 30 cases in which neuroArm was used since the implementation of the safety review.

NeuroArm includes numerous safety features to minimize hazards, including inadvertent motion, loss of function, electric shock or burn, and contamination. MacDonald, Dettwiler and Associates ensured that neuroArm was built to both aerospace and medical standards. Aerospace regulations are more specific when it comes to robotic function and quality, and medical standards ensure that patient safety is at the forefront of design. During surgery the operator is responsible for tool manipulation, and the assistant at the surgical site ensures that no accidental collisions occur when the tool is out of microscopic view. The entire team shares responsibility for safety in the OR and can use their headsets to immediately communicate any difficulties or potential hazards. In the event of a power outage, a braking system is used to stop the actuators, allowing the manipulators to be manually extracted from the surgical site. Other safety features include patient position monitoring, no-go zones, and MR-visible markers within the tools for verification imaging to assess the accuracy of tool overlay.

The graded approach to clinical use accommodates the surgeon’s learning curve and confidence level with new complex technology. Preclinical testing included use of a neuroArm trainer, in which simulations were created for biopsy and suturing, and to reflect precision and accuracy. The next stage of preclinical testing used an animal...
model. Hepatic lobectomy, pancreatectomy, bilateral nephrectomy, and removal of the submandibular gland were performed on rats using microsurgical technique and neuroArm. Once surgeons were confident performing virtual and animal surgeries, neuroArm was applied clinically.

Experience helps determine such factors as the positioning of the robot, how to move the manipulators within the surgical corridor, and how to compensate for the difference in the robot’s motion from the movement of the hand controllers. The learning curve was increased by the different pathologies across the 35 cases. This variation makes it especially important to become comfortable with each step of the operating procedure—positioning, draping, and performing an incision—before continuing to the next stage. It took approximately 20 cases for the surgeon to feel comfortable performing the majority of a microdissection with neuroArm. With each subsequent case there was a notable increase in surgeon confidence using neuroArm, and the procedure became smoother. This graded approach maximizes the safe and effective use of the robot during surgery. Only one patient suffered increased deficit following surgery: the patient with a recurrent right prepontine dermoid cyst experienced transient right facial nerve palsy. This was also noted following his first surgical procedure several years prior.

The graded approach also allows potential problems in the software or hardware to be identified and removed. NeuroArm is a prototype, and the current construction of the next generation of neuroArm is benefitting from this clinical experience. A randomized control trial to prove efficacy will need to be conducted with the next generation, as by that point both the learning curve of the surgeons and the hiccups that arise from creating and integrating a complex technology into the OR will have been accommodated. Additionally, there will be more than one system, allowing for sufficient numbers of patients to conduct such a trial. Thus the trial will more accurately reflect the capabilities of the technology.

Perhaps the greatest advantage of a surgical robot is its capability for smooth movement. Tremor filters ensure that the machine performs with steadiness and precision. This ability to combine the human surgeon’s actions with the exact motion of a machine increases accuracy on a microscopic scale. Additionally, the robot does not suffer fatigue related to positioning, which means that it can reach over retractors more easily than human surgeons and can operate on patients positioned unusually to expose the pathology.

One of the potential pitfalls of using a surgical robot is the lack of human dexterity. Commands from the surgeon go through a computer processor before the manipulators respond, which creates a delay, albeit one so slight that the surgeons could not perceive it during the 35 cases. Although the robot has great precision, it cannot replicate human speed, which is predicated on experience. The maximum neuroArm speed is 200 mm/sec while carrying a 750-g object. Additionally, surgeons move the robot with caution as they become accustomed to the unique responsiveness of surgical robots. This results in slower movement during surgery. NeuroArm’s human-machine interface, combined with the onsite surgical assistant, allow the surgeon to compensate for the lack of robot dexterity while capitalizing on the machine’s high level of accuracy and precision.

In the initial cases, a visual system with binocular stereoscopic display was used. The limitation of this type...
of display unit is that the operating surgeon loses peripheral vision when looking into the display. This means that the surgeon cannot visually orient his or her hands to the tools on the display. The 2011 upgrade to a 3D high-definition monitor restored the surgeon’s peripheral vision, and as a result the surgeon found it much easier to operate the neuroArm hand controllers. While vision is just one component of spatial awareness, it provides an important cue for the surgeon coordinating personal movement to the motion of neuroArm’s manipulators, especially considering that while neuroArm does provide haptic feedback, that feedback is presently limited by the capabilities of technology. The current hand controllers supply 6 degrees of freedom for position and 3 for force feedback to the surgeon, while the human hand is able to perceive many more degrees of freedom in terms of force and torque.\textsuperscript{16,17} In addition, the surgeon uses body position sense, or proprioception, to understand the relative position between the tool in the left hand and the tool in the right.\textsuperscript{14,15} With a robot, the surgeon receives haptic feedback from the tool tips but not from the rest of the manipulator, leaving a gap in spatial awareness normally occupied by the arms and shoulders. For now, visual information must help the surgeon compensate for that gap. Designing surgical robots to accommodate, or even augment, human perception can greatly facilitate the success of surgical integration.

NeuroArm has not yet been used to obtain a biopsy specimen within the aperture of the magnet. All of the initial 35 cases were microsurgery. The current size of neuroArm allows for only one manipulator to be inserted into the magnet. While surgery is possible with only one manipulator, performance is improved with two. The next generation of neuroArm, neuroArm II, is already in development. The manipulators will be 25\% smaller than neuroArm I, which will allow both manipulators to fit into the magnet aperture. The smaller manipulators will also be able to reach back outside the magnet to pass tissue to a nurse, a movement that the current neuroArm would have trouble performing. In addition to the smaller size, material selection has changed to decrease the impact of the robot on image quality. For instance, titanium joints will be changed to polyetheretherketone, a plastic used for engineering applications.

Based on these 35 cases it seems clear that a robotic workstation could become central to surgical procedure. It allows the surgeon to manipulate imaging data from a centralized location. The surgeon gains control over the various technologies in the OR, and is able to manipulate these elements during surgery. The robot returns the surgeon to the surgical site. Eventually the workstation could be connected to the Internet to access global knowledge and interact with other medical centers. As the amount of technology in the OR increases, the workstation will provide a streamlined solution to the operation of the various technological elements present. Much like the space

![Hazard Diagram](Fig. 6. Hazards related to the introduction of robotics into neurosurgery. Described are the causes of the hazard, the control used to mitigate the risk, and the remaining challenges related to the hazard.)
Merging machines with microsurgery

industry uses command center workstations to monitor and interact with unmanned spacecraft, the surgeon will be able to control the entire surgical environment from a single workstation.3

The digital nature of robotics allows both surgical playback and case rehearsal, which will be beneficial tools for surgeon education. Virtual learning can provide practice for a larger variety of cases than a resident currently experiences.4,5 Even fully trained neurosurgeons will appreciate the benefits of case rehearsal.

NeuroArm has the potential to improve the practice of microsurgery, particularly as technological advances allow further refinements in robotic design. When combined with a workstation, surgical robots bring Information Age technologies into the OR, allowing surgeons to access and manipulate patient data without interrupting the rhythm of surgery. Machines are developing toward the enhancement of human senses, continuing the progress of surgery toward the cellular level.

Disclosure

Garnette R. Sutherland holds shares in IMRIS, the Canadian company manufacturing and distributing both intraoperative MRI and neuroArm technology. His name is listed on many of the founding patents of IMRIS. Liu Shi Gan, while located at the University of Calgary, received financial support from IMRIS and currently is a postdoctoral fellow at IMRIS. This work was supported by grants from the Canada Foundation for Innovation, Western Economic Diversification (Canada), and Alberta Advanced Education and Technology.

Author contributions to the study and manuscript preparation include the following. Conception and design: Sutherland. Acquisition of data: all authors. Analysis and interpretation of data: Sutherland, Lama, Wolfsberger, Zareinia. Drafting the article: Sutherland, Gan. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Sutherland. Administrative/technical/material support: Sutherland. Study supervision: Sutherland.

Acknowledgment

Appreciation is extended to Claire Lacey, B.A., M.A., for her considerable help in preparing this manuscript.

References


Supplemental online information:


Address correspondence to: Garnette Sutherland, M.D., University of Calgary, Health Research Innovation Centre, 3280 Hospital Drive NW, Calgary, Alberta T2N 4Z6, Canada. email: garnette@ucalgary.ca.