The Development of Robotics for Interventional MRI

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- Neurosurgery • Robotics • Intraoperative MRI
- NeuroArm • Human machine interface

Progress in neurosurgery has, to a large extent, paralleled advances in technology. With the introduction of the operating microscope and microsurgical technique, surgical corridors became increasingly narrow, accelerating the development of complimentary instrumentation.[1] The inventions of CT and MRI provided unprecedented preoperative lesion localization, allowing neurosurgeons to plan more precisely targeted approaches.[2–5] These imaging techniques, in addition to enabling lesion localization, gave clinicians better insight into diagnosis prior to surgery. The 1990s saw the introduction and widespread use of computer-based image guidance systems that allowed intraoperative surgical navigation based on preoperative images. Due mainly to the problem of brain shift associated with craniotomy and surgical dissection, CT and MRI technologies were brought into the operating room and integrated with neurosurgery.[6–10] The integration of robotic technology into surgical procedure represents the culmination of a logical progression that takes full advantage of these innovations. Robotic technology offers the potential for increased precision and accuracy and, when coupled with ongoing advances in neuroscience and the integrative and executive capacity of the human brain, provides an unparalleled opportunity to improve neurosurgical outcome.

This article presents a brief review of the evolution of neurosurgical robots, the challenges associated with the development of a magnetic resonance (MR)–compatible image-guided robot, and an overview of the manufacture, integration, and initial clinical experiences of such a robot, neuroArm.

EVOLUTION OF THE NEUROSURGICAL ROBOT

The first neurosurgical robots performed only simple, well-defined tasks. One of these was the Programmable Universal Machine for Assembly (PUMA; Advance Research and Robotics, Oxford, Connecticut), an industrial robot adapted for neurosurgery.[11] It had a single arm with six degrees of freedom (DOF). With a personal computer, the arm could be programmed to move in line with the planned trajectory or be moved passively into position. Preoperative CT images, taken with the Brown-Roberts-Wells head frame, were used to determine stereotactic coordinates and to provide three-dimensional (3D) reconstructions of the target lesion and surrounding anatomical structures in relation to the probe. In 1991, Drake and colleagues[12] reported the successful application of the PUMA 200 robot as a retractor holder in the resections of thalamic astrocytomas in six children (**Fig. 1**). Safety concerns with regards to the use of an industrial robot in surgery halted further development of PUMA for applications related to neurosurgery.

NeuroMate (Integrated Surgical Systems, Davis, California), developed specifically for neurosurgery, was intended for stereotactic procedures with image guidance.[13] NeuroMate has a single

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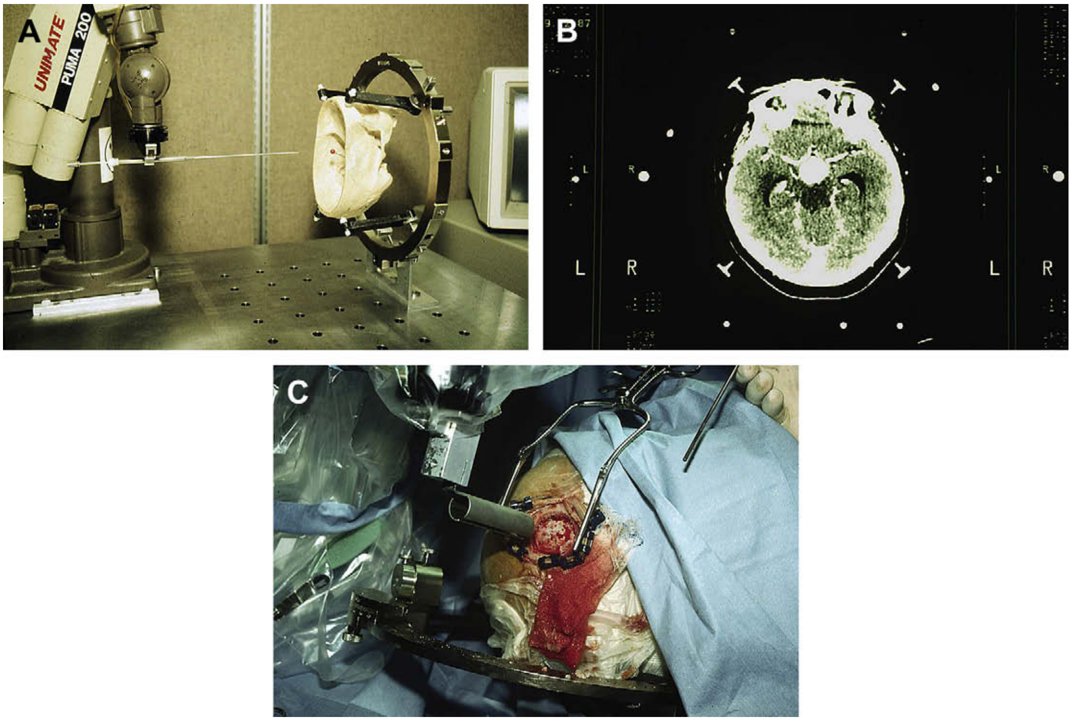

Fig. 1. The PUMA 200 is a six-DOF manipulator capable of moving at a peak velocity of 1 m/s while carrying a payload of 1 kg. (*A*) The PUMA 200 arm directs a probe towards the planned target in a skull. (*B*) A preoperative CT scan taken with the Brown-Roberts-Wells stereotactic frame shows a thalamic astrocytoma. Stereotactic coordinates are calculated from the preoperative imaging. (*C*) The PUMA arm, gripping a retractor, moves into position in the surgical field. (*Courtesy of* James Drake, MD, University of Toronto, Canada.)

arm with five DOF and is capable of gripping or stabilizing surgical instruments, such as cannulas and biopsy needles (**Fig. 2**). Using preoperative CT or MRI, the target lesion and trajectory are defined at the computer workstation and the robot arm is commanded into position. NeuroMate is compatible with both frame-based and frameless stereotaxy; the frameless mode uses an ultrasound registration system. NeuroMate, the first robot approved by the Food and Drug Administration for use in stereotactic neurosurgical procedures, has been used for tumor biopsies and various functional procedures, including electrode placement for deep brain stimulation.[14]

Evolution 1 (Universal Robot Systems, Schwerin, Germany) was designed to enhance positional accuracy and precision of movement in microsurgical and neuroendoscopic procedures. Evolution 1, a hexapod robot with six DOF,[15] operates using high-precision linear axes and joints and has an absolute positional accuracy of 20 μm and motion resolution of 1 μm while carrying payloads of up to 50 kg. The mobile platform can accommodate a variety of surgical instruments, including an endoscope. During surgery, the surgeon at the workstation uses a joystick to direct the robot with the aid of neuronavigation and preoperative MRI. Evolution 1 has been used in the positioning and maneuvering of ventriculoscopes in neuroendoscopy.[15] Functioning in a similar role in endoscopic transsphenoidal resections of pituitary adenomas, Evolution 1 enables surgeons to operate using two instruments simultaneously.[16]

The integration of intraoperative image guidance with neurosurgical robots followed. Minerva (University of Lausanne, Switzerland),[17] a robot with a five-DOF arm, was designed to perform stereotactic neurosurgical procedures within the CT scanner. Minerva occupied a position at the head of the operating table, behind the CT scanner, so that its arm could work within the gantry. Successive CT image acquisition during the procedure updated the instrument position in near real-time, thus providing intraoperative image guidance. The system automated the tasks of making skin incisions, drilling bone, performing dural perforations, and manipulating probes.[18] Applications of Minerva in stereotactic tumor biopsies were successful.[17,18] Even so, the project was discontinued, apparently because of CT imaging