Review

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Robotics in Cranial Neurosurgery, 35 Years of Evolution

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ABSTRACT We reviewed the experience of robotic devices in cranial neurosurgery for 35 years. The brief history is represented, prerequisites for robotics development are specified. The most popular devices are listed, which are used for surgical instruments positioning and remote manipulations. We pointed key robotic features, main results of their application, showed advantages, shortcomings and ways to resolve some problems. The accurateness of robotic systems is shown in comparison with frame-based stereotactic surgery. The main trends in robotic development in the future are described as well.

Keywords: robotic device, cranial neurosurgery, NeuroMate, Rosa, Renaissance, NeuroArm

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CT – computed tomography
FDA – Food and Drug Administration
MRI – magnetic resonance imaging
USA – United States of America

INTRODUCTION

The development of neurosurgery follows two directions. Firstly, modern diagnostic methods and new surgical instruments expand the indications for surgery for diseases that were previously considered incurable. Secondly, technical innovations make it possible to perform interventions through minimally invasive approaches. Microvascular anastomosis, perineural suture in the depth of the wound, removal of the tumor through a narrow access require a lot of experience and physical resource from the surgeon. Manipulations at the millimeter level are possible using optical magnification. But movements at the submillimeter level are limited by a physiological tremor comparable in amplitude. Long-term high-precision operations lead to fatigue of the surgeon's hands. A narrow and deep wound is often poorly lit. All these factors predispose to the development of robotic systems that facilitate the performance of such operations.

Another area of medical robotics is the creation of devices for precise positioning of surgical instruments. In cranial surgery, this is important when taking a biopsy, locating small deep tumors and caverns, removing hypertensive hematomas and installing intracerebral electrodes. Existing navigation systems are also designed to solve similar problems. But the error of frameless navigation is 2–4 mm [1]. Frame stereotaxis is more accurate (with an error within 1 mm) and is inconvenient for use [2]. Combining millimeter accuracy with operating comfort is the goal of developing precision positioning robots.

HISTORY

Many early medical robots were developed with the participation of the National Aeronautics and Space Administration (NASA) and the United States Defense Agency (USA). The first operation using robotic assistance was performed in 1985 by Kwoh Y.S. The industrial robot Puma 560 (programmable universal machine for assembly) developed by General Motors for non-medical purposes was used. The robot had 6 degrees of freedom and performed frame stereotactic positioning of the biopsy needle. The device calculated the exact location of the target faster than a human and directed a surgical instrument at it [3, 4]. The first robot certified in the USA for stereotactic procedures in neurosurgery was described in 1987 and was called NeuroMate [5]. In terms of accuracy, it was comparable to frame stereotaxis, and it was used in operations for movement disorders.

The complexity of neurosurgical operations hindered the rapid development of robotics [6]. In 1990, Adler J.R. described the use of a radiosurgery robot that positioned a linear accelerator to match the patient's slight movements. Later, this device became known as a cyberknife [7]. In 1991 Drake J.M. used the Puma industrial robot to remove 6 thalamic astrocytomas in children [8]. The development of these robots was based on the navigation method. In 1991, Davies B. used an actively moving apparatus in soft tissue surgery. He was a prototype called "Probot", which was then used in urology for transurethral prostatectomy [9]. A four-axis robot was first described in 1992 by Benabid A.L. [10].

SRI International's first telesurgical robot for open abdominal surgery was piloted by Hill J.W. in 1994. It was then modified for laparoscopic abdominal surgery [11]. Next, robots The Zeus and daVinci were developed, originally intended for cardiac surgery. In 2001, a remote operation was performed using a controlled robot - laparoscopic cholecystectomy, during which the surgeon was at a distance of 14,000 km from the patient. The operation lasted 54 minutes and ended with a good outcome [12]. In neurosurgery, such operations were initially performed only on laboratory animals and cadavers. A vascular suture was usually applied [13].

NeuRobot was the first "master-slave" robot in neurosurgery that was used to simulate neurosurgery on a cadaver. It was used to perform endoscopic triventriculostomy and dissection of the lateral fissure in 2002 [14]. In 2003, Goto T. et al. first used it in the operating room, removing part of an atypical meningioma [15].

All medical robots can be classified into four types: active devices for determining the location of the target, passive devices for performing remote manipulations, autonomous devices and auxiliary robotic systems.

ROBOTS FOR PRECISE POSITIONING

These devices perform precise positioning of a surgical or diagnostic instrument in the surgical wound. The mechanism of their work is similar to neuronavigation. Before the operation, preoperative images with neuroimaging data are loaded into the robot workstation. After that, the computer program generates a virtual model of the patient's head. Intraoperatively, after laying the patient and rigidly fixing his head, the real surface of the patient's head and its virtual model are compared. For these purposes, radiopaque markers attached to the head are often used. Knowing the coordinates of the patient's head and the target located in it, the robot brings the working tool to it with the help of electric motors [4].

For these purposes, 8 robots are used in cranial neurosurgery. Six of them are used at the main stage of the operation, and two for craniotomy.

NeuroMate is a robotic arm with 6 degrees of freedom. It was developed by Integrated Surgical Systems in 1987 [4]. After being approved by the Food and Drug Administration (FDA) in neurosurgery, it was first used in 1997. The accuracy of its installation in clinical practice is 0.86–1.77 mm, which is comparable to the results of frame stereotaxis. The device was used to perform biopsies with an accuracy of 86%, to place electrodes for invasive corticography and deep subcortical stimulation. Its use for targeted chemotherapy is described. The disadvantages of the robot are its large size, high cost, and the complexity of learning to work with it [16–19]. When inserting stereoelectroencephalography electrodes in combination with the frameless Neurolocate system, the robot demonstrated submillimeter accuracy that exceeded the results of frame stereotaxis (0.67 mm vs. 0.76 mm) [20].

SurgiScope created company Intelligent Surgical Instruments and Systems (ISIS, France) [19]. It is an operating microscope with a ceiling mount on rails for precise positioning. Has 7 degrees of freedom. The device error is 1.5–1.6 mm. The first application was described in 2003. Its accuracy in taking biopsies is 98% [21], and it is 100% in ventriculostomies [22]. The robot was used to install electrodes for stereoelectroencephalography. Its disadvantage is its large size [17].

ROVOT-m was created by Synaptive Medical (Canada). It is a system for automatic positioning of the exoscope under the control of neuronavigation. The device was used to remove intracerebral hematomas, tumors, vascular malformations, clip aneurysms, and treat neurovascular conflict with good functional outcomes [23].

Rosa was designed by MedTech (France). It is a robotic hand with 6 degrees of freedom and an imitation of touch. It was approved by the FDA in 2009 [24]. It is based on a mobile platform rigidly fixed to the patient's skull. Used in frame and frameless modes. The first description of the application in neurosurgery is dated 2012. The robot was used to place electrodes in parkinsonism (a positive effect was described in 55%), to take biopsies (100% informative value, 97% accuracy), to place electrodes for invasive corticography, stereotaxic radiofrequency thermal ablation, in endoscopic ventricular and transnasal surgery, and also in craniofacial reconstructive surgery. Depending on the method of registration and the location of the device in relation to the target, the positioning error varies from 0.52 to 1.75 mm [25–27]. The accuracy of operations with the use of the Rosa robot is higher than with the use of frame stereotaxis (0.76 mm versus 1.11 mm). When placing electrodes in the subcortical nuclei, the maximum error was 1.52 mm, while with mechanical navigation in 9% it exceeded 2 mm. Robotic assistance reduces the duration of the surgical intervention in comparison with frame stereotaxis. This difference is most clearly seen when locating several targets, since the robot moves between them very quickly without the need to rewire the system [24]. The disadvantages of the unit are its large size, the need to be located next to the patient's head, high cost and complexity of development [17].

Renaissance (SpineAssist, Mazor X) developed by Mazor Robotics Ltd. (Israel). The robot of the first generation is called SpineAssist, the second generation is Renaissance, and the third generation is Mazor X. The first two devices are miniature devices with 6 degrees of freedom, rigidly fixed to the skull, Mazor X is a robotic arm. In brain surgery, the robot began to be used in 2015. The error of work does not exceed 1.0–1.5 mm. When performing biopsies, the accuracy is 89%. Its main advantage is compactness. It is especially convenient to use the robot to take several adjacent biopsies. The disadvantages of the unit are a small working area, which requires manual remounting when displaced, as well as the need to perform computed tomography (CT) for preoperative registration (the reference frame is incompatible with magnetic resonance imaging (MRI)) [17, 28]. The Renaissance robot is most often used in neurosurgery; about 10,000 operations have been performed with its help [29].

iSYS 1 was created by iSYS Medizintechnik (Austria). This is a miniature robot with 4 degrees of freedom. Initially it was used in invasive radiology, later it was used in neurosurgery, when taking biopsies, ventriculostomy [30] and electrode implantation in epilepsy [31]. The first publication about its use was published in 2016. The error of the device in experiments on a phantom and cadavers is 0.6–0.8 mm. The accuracy of the instrument in vivo is 1–2 mm. The advantages of the robot are its small size, low cost, and ease of use, while the disadvantage is the need for manual reset when changing the manipulation area (for example, when taking several biopsies or installing deep electrodes) [30–32].

A robot based on CAD-CAM technology (computer-aided design/computer-aided manufacturing) is a software and hardware system designed to perform complex craniotomies. With the help of a bur, it is able to impose milling holes and grind the bone. The device has 2 important functions. The first provides for the presence of feedback depending on the data of electroneuromyography: the device automatically stops near the facial nerve. The second option provides for the concept of a safe zone: the robot is not able to cross the protected border allocated before the operation. The device was tested on cadavers when performing a translabyrinthine access. The positioning accuracy of the robot was 1 mm, and the duration of the craniotomy was 2.5 minutes [33].

Craniobot is represented by LabMaker (Germany). It is an experimental three-axis robot for performing craniotomies. Developed on the basis of a wood cutting machine used for handicrafts. Positioning the drill at the desired point, the robot determines its coordinates during CT, calculates the thickness of the bone in this place, and then imposes a burr hole using a bur. The high accuracy of the apparatus prevents damage to the dura mater and brain structures. In experiments on mice, in 97% of the experiments, the positioning error was less than 6 μm. It took 4 minutes 40 seconds to place 40 mini-holes in the skull, and 50 seconds to perform a 3 mm craniotomy. The advantages of the device are its low cost and the ability to program using G-code scripts. The robot has not yet been used in clinical practice [34].

All modern robots have positioning accuracy comparable to or better than other stereotaxic devices. However, their use often leads to complications (8–10%) [17, 35–39]. A larger number of hinges increases the number of degrees of freedom and the accuracy of the device, but this increases the number of motors, complicates the design and algorithm for positioning the device [4]. The constant use of robots for precise positioning leads to the loss of skills of the neurosurgeon. This is of no clinical significance in the presence of robotic systems. However, if the possibility of their use is lost, the quality of surgical interventions may decrease [40].

Other robots (PUMA, Minerva, Zeiss MKM, Telerobot, Acubot, Evolution 1, RobaCKa, NeuroMaster, PathFinder, LWR -II, NISS, STIN, CRANIO) are of more historical interest, are currently out of production, and are not used in neurosurgery [17].

ROBOTS FOR REMOTE MANIPULATION

These software and hardware systems, operating as a "master-slave", are an intermediate link between the surgeon and the manipulators. When using them, the operator works exclusively with computer joysticks based on the image from the video cameras displayed on the monitor, and does not touch the surgical wound. All surgical manipulations are performed directly by the robot using micromanipulators [4].

These robots have the following advantages.

1) Allow to perform manipulations by a surgeon located at a great distance. An experienced surgeon can operate on patients in different hospitals located thousands of kilometers away [12].

2) They can work in dangerous conditions, for example, in X-ray conditions [41].

3) Eliminate hand tremor, increase the accuracy of movements due to the fact that the amplitude of the movements of the surgeon's hands is scaled many times into more subtle manipulations [41, 42].

4) They make it possible to simultaneously firmly hold several instruments (more than two), for example, an endoscope camera, an irrigator, an aspirator, a clamp, a needle holder [43].

5) They allow you to move the tool only in the permitted zone, even with the application of force [42].

The main disadvantages of such robots:

1) take a long time to master;

2) significantly increase the duration of manipulations;

3) are not able to accurately convey the sense of touch of the patient's tissues;

4) high cost;

5) are large and inconvenient to use [44].

The following robots have been developed to perform remote neurosurgical manipulations.

NeuRobot was developed at Shinshu Medical University (Japan) to perform minimally invasive surgeries. This is a controlled robot, all manipulations with the patient are carried out through a cylindrical tube with a diameter of 10 mm. A stereoendoscope with a diameter of 4 mm is passed through it, 2-3 micromanipulators, the tube has channels for irrigation and aspiration. Working instruments with a diameter of 1 mm have 3 degrees of freedom, include microclamps, microhook, microneedle, bipolar coagulator, aspirator and laser. The manipulation accuracy reaches 20 μm. The robot was tested when performing dissection of the lateral and interhemispheric fissures, ventriculocisternostomy on a corpse, encephalotomy, vasotomy, and hemostasis on rats (the distance between the micromanipulator and the control unit was 40 km), as well as when removing part of the meningioma of the cerebellum in a patient with continued tumor growth (part of the tumor resected with a laser). At the moment, the efforts of developers are aimed at increasing the speed of the network to reduce the delay when using the robot [14, 15, 19, 45].

MM-3 robotic platform is developed by Akio Morito's group at the University of Tokyo. It consists of 2 micromanipulators with dynamic scalability of the amplitude of movements and a stereomicroscope. The system is designed to perform microvascular manipulations at the submillimeter level under the control of a microscope, for example, the imposition of a microvascular suture. The size of such objects is comparable to the amplitude of the physiological tremor of the surgeon's hands. The scalability of movements and tremor suppression make such procedures possible. Initially, the device was used to make fistulas on artificial vessels. Microtubules 0.3 mm in diameter were used for end-to-end anastomosis, and 0.5 mm were used for end-to-side anastomosis. The system was then used to perform 20 anastomoses on rats and to perform various approaches on cadavers. The use of the robot reduced the error by a factor of 2 (from 80 to 44 μm). The system has high accuracy, but its use significantly lengthens the operation compared to the time spent by an experienced surgeon. This applies to both the entire procedure and individual micromanipulations. Work experience can solve this problem [46, 47]. The main difference between the MM-3 platform and other robotic systems is the ability to customize the interaction between the operator and the executable device. There are 4 operating modes. In the fixed mode, the scalability of movements does not change throughout the manipulation; in the target mode, it increases with decreasing distance between the manipulator tips and the target; in the executed mode, it increases with a smaller distance between the manipulator tips; in the high-speed mode, it depends on the pace of the surgeon’s work (decreases with increasing). In the course of experimental testing, the most comfortable and fastest mode turned out to be the executable mode in the range of 0.2–0.5 (the amplitude of movement of micromanipulators is 2–5 times shorter than the movements of the operator's hands). Currently, work is underway to automate the choice of scaling mode based on the experience of the surgeon [48].

NeuroArm is the most advanced robotic control system. It was developed at the University of Calgary (Canada) in 2001 [4]. It consists of two manipulator arms connected to the workstation via a controller. Each manipulator has 7 degrees of freedom and pressure sensors at the working ends. The device allows performing stereotaxic and microsurgical manipulations in a magnetic field with induction up to 3.0 T. The system provides binocular vision through two video cameras and polarized glasses. The microphone allows the surgeon to hear sounds in the operating room. A tactile sense of feedback is achieved by attaching 2 pressure sensors to the robot manipulators, which evaluate the applied efforts in 3 projections, although the resulting sense of touch is not ideal [19]. The robot contains a tremor filter with the ability to set different cutoff frequencies. The speed of the robot arm movement varies from 1 to 200 mm/s. The scalable scale allows you to change the amplitude of its movements from 1/1 to 1/20. A special option allows the robot to draw a straight line even if the surgeon's arm is not moving in a straight line. The NeuroArm has an accuracy of 50 microns, which is close to surgery at the cellular level. The robot steadily holds surgical instruments and allows performing surgical manipulations through a narrow anatomical corridor. The surgeon is located behind the workstation. Several monitors display the image of the intraoperative MRI and the surgical wound. It is possible to connect to the Internet to get help information. When the movement of the manipulator deviates from the planned trajectory, autostop is activated. Also, the surgeon can arbitrarily block the movements of the manipulator by pressing the pedal. An interesting option is the possibility of designing a virtual surgical corridor during MRI, after which all manipulations of the robot will be allowed only within its limits. Even if the surgeon applies force, the manipulator will not cross the limit line. The device was tested on phantoms, laboratory animals and cadavers. Splenectomy, nephrectomy, and removal of the submandibular gland were performed with equal accuracy in rats with and without a robot. In clinical practice, the device was first used in 2008 to remove a brain mass in a 21-year-old patient. After FDA approval, 35 patients with tumors, cavernomas, and brain abscesses were operated on using a robot. The surgeon was outside the operating room, the assistant was in front of the NeuroArm. In only one case, it was necessary to stop the operation using a robot and switch to conventional surgery due to a narrow corridor that limited the simultaneous view of the surgeon and assistant. The average duration of operations was 4.5 hours, which is comparable to conventional surgery. The use of a telerobot requires long-term training: the surgeon gains confidence in working with it after performing 20 operations [41, 43, 49–51]. In total, more than 1000 operations were performed using the robot: hematomas were removed, wounds were sutured, biopsies were taken, and cisternal dissection was performed [19].

ROBOCAST was developed by KUKA Roboter GmbH (Germany). It is a combination of two previously created KUKA LWR 4 robots. These are 2 manipulators operating in two modes. In an autonomous version, the robot is used for precise positioning of instruments in the surgical field. In remote mode, peripheral devices repeat the actions of the surgeon, compensating for any movements of the skull [29].

Robot-assisted microsurgery system (RAMS) was developed in a joint program of the Jet Propulsion Laboratory of the California Institute of Technology and Microdexterity Systems Inc (USA). It is a remote-controlled system with 6 degrees of freedom. The device is compatible with MRI, designed for microsurgery, including neurosurgery, ophthalmology and plastic surgery. The robot was used in experimental endarterectomy in rats, but the use of the device significantly increased the duration of the operation [19].

Da Vinci robot is a product of Intuitive Surgical (USA), designed to perform endoscopic operations from mini-accesses. Consists of 2 cameras for stereoscopic vision and 2-3 manipulators for fixing working tools. It has the function of filtering tremor and scaling movements. Initially, the device was developed for cardiac surgery, but did not find wide application in it, since cardiac surgeons without a robot can perform all the same manipulations with the same accuracy, but faster. The Da Vinci robot is used in laparoscopic surgery, urology and gynecology. In neurosurgery, this robot was used for transnasal endoscopic closure of dural defects in cadavers [52], arachnoid dissection, and vascular suture on the M1 segment of the middle cerebral artery in cadaveric experiments [53]. The device was used in spinal neurosurgery for removal of the odontoid process of the 2nd cervical vertebra, spinal neurinoma, anterior interbody fusion, and intrauterine meningocele repair [4]. The Da Vinci robot is bulky, uncomfortable, and has several artificial tool holders that obstruct the view. Its use in key-hole neurosurgery is possible only with a wound depth of up to 2 cm. Further, the instruments interfere with each other and do not allow the endoscope to be immersed. The device was not originally intended for use in neurosurgery and was not widely used in it [35, 44, 54]. One way to solve the problem could be to reduce the diameter of the working tools. But long narrow manipulators under the influence of external forces are able to deviate from the intended trajectory, which reduces the accuracy of manipulations [4].

AUTONOMOUS ROBOTS

It is possible to develop a robot that makes decisions independently in two ways. The first (explicit) is based on programming a sequence of actions. The second (implicit) one is based on machine learning. Given the many different factors that need to be taken into account when developing an algorithm for the operation of the system, the second method seems to be the most relevant. Currently, autonomously operating robots in neurosurgery have not been created [55]. In abdominal surgery, the device STAR (Smart Tissue Autonomous Robot) is described, designed for anastomosis. The device is capable of operating in two modes: manual and automatic. In the stand-alone version, the computer independently selects the suture site depending on the contour of the incision. When applying an anastomosis to the intestines of a pig in automatic mode, the robot performed the experiment more accurately and 4 times faster than a human [56].

The process of autonomization of robots can be implemented to varying degrees, from partial to complete. With partial autonomy, the surgeon controls the operation of the machine. The creation of a device that independently makes decisions is based on the development of computer technologies, in particular, deep learning methods. The use of such devices is especially important when human intervention is impossible (dangerous conditions, hostilities, great distance). Their manufacture for medicine is predicted only in 50–100 years [55].

AUXILIARY ROBOTIC SYSTEMS

This is the **iArmS device,** which is a robotic armrest to support the surgeon's hand. Developed at Shinshu University (Japan). It is an improved version of the previously presented EXPERT prototype. Without a motor, the device does not accurately position the surgical instrument. Its task is aimed at automatically following the operator's forearm. Technically, this is done by means of a magnetic field between the device and the electromagnetic bracelet on the surgeon's hand. The robot relieves fatigue, stops tremor, increases the comfort of work and reduces its duration [19, 57]. The device was tested in cranial microsurgery and endoscopic transnasal operations. Unlike passive armrests, the robot automatically follows the surgeon's hand without distracting him from the operation. There are options for right-handers and left-handers. A force of more than 10 kg stops the system. Additionally, there is an emergency immobilization button. The disadvantages of the robot are its large size and high cost [58].

CONCLUSION

Despite significant progress, modern medical robotics is only at the initial stage of its development. While precise positioning robots have already passed clinical trials, remote manipulation devices have mostly been used only on phantoms, cadavers, and laboratory animals. The development of new technologies, computer systems, network protocols and technical ideas, coming from practicing surgeons as well, are the basis for progress in this direction. Without taking into account the cost of equipment, the main disadvantage of robots at the current stage of their development is the lengthening of the surgical intervention. This is associated with the unnatural control of the automaton in comparison with direct surgical manipulations. Mastering a robot takes a long time to learn, but it pays off in the long run by reducing the invasiveness of operations.

With the widespread development of machine learning, the most promising is the creation of autonomous robots capable of making decisions on their own. Large data companies have created and are constantly updating software products that facilitate the process of deep learning. In medicine, their implementation is most represented in radiology, and computer programs are being actively developed to facilitate diagnosis and treatment planning. The combination of artificial intelligence with mechanical engineering is the basis for creating autonomous robots of a new generation. The greatest difficulty in training such systems is the lack of large databases. Improving the algorithms for designing neural networks, combined with the accumulation of arrays of surgical information, will make it possible in the future to create robots that are not inferior to an experienced neurosurgeon in the quality and speed of performing surgical interventions.

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