Introduction to Robotics in Skull Base Surgery

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1.1 Introduction

The term "robot" was coined by Capek in 1920 to describe an automated machine used to replace human laborers [1]. Since then, there has been rapid progress in "robotics," where automated machines are designed to perform hundreds of functions in different fields, including medicine [2–4]. Present-day robots are designed to carry out not only simple tasks but also complex procedures requiring serial steps [2] via computer programming. These tasks can be automated, semi-automated, or passive, depending on the degree of human input during the robotic action [5–8]. In surgery, the use of robots has evolved dramatically from passive machines designed just to help surgeons perform certain steps more precisely, to advanced semi-automated robots requiring physician input only at certain points [9–11]. The

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dramatic evolution of robotics in surgery has also enabled surgeons to perform not only local but also remote procedures via telerobotics [12–14].

The use of robotic surgery has increased dramatically during the past three decades [2]. A common surgical robot called the da Vinci surgical system (Intuitive Surgical, Sunnyvale, CA, USA) was designed to perform minimally invasive surgeries [15]. Since its Food and Drug Administration (FDA) approval in 2000, the da Vinci video endoscopic system has been increasingly adopted, especially in urology, gynecology, and otolaryngology [16–19]. This robotic surgical system has conferred several benefits: a wider range of motion within narrow corridors, motion scaling, 3D visualization of the surgical field, better comfort for the surgeons, and improved postoperative recovery [15, 20–23]. The da Vinci was the only commercially approved surgical system until 2020, when the FDA approved the Medrobotics Flex robotic system for use in different surgical fields, especially the head and neck [24].

Robotic surgery in neurosurgery dates back to stereotactic biopsy [25]. Thereafter, both automated and semi-automated robotic systems were developed and adopted for biopsy-taking from deep brain structures, deep electrode placement, placement of cochlear implants, and many other procedures requiring millimeter accuracy [26–28]. Four different categories of robots are used in neurosurgery: those designed for navigation and placement of depth electrodes, those designed for skull drilling, NeuroArm, and those (e.g., the da Vinci system) used to perform surgical procedures [25, 29, 30]. This chapter will focus on the last type, as used for skull base surgery.

1.2 Robotics in Skull Base Surgery

Although the rate of robotic surgery has increased dramatically in many surgical fields, as mentioned, progress in neurosurgery has been slower [31]. For example, there are relatively few data in the literature about the use of the da Vinci system in neurosurgery [31]. Notably, the da Vinci and the Medrobotics Flex robotic systems were not approved for skull base surgery [32]. This was because of their large size, long set-up time, and poor ergonomics, so it was not feasible to use them in the very tight corridors of the skull base [32]. Moreover, many studies evaluating skull base robotic surgeries were conducted on cadavers and/or animal models, and the results were discouraging [33].

Despite the slow growth of robotics in skull base surgery, neuroscientists are endeavoring to improve their development, enhance their adaptability, and make it possible to adopt them. Robotics fits the aim of this type of surgery perfectly, i.e., maximizing the exposure of a skull base lesion using the least amount of brain retraction [34]. This kind of surgery is challenging owing to the complex anatomy of skull base targets, their deep-seated location, and the proximity of critical structures. Robotics can provide more direct and less invasive access to the skull base than the conventional open surgical approach, avoid making cranial or facial incisions, and minimize brain retraction [32].

To date, the vast majority of skull base surgical procedures using robotics have been conducted to remove pituitary tumors [35–37]. Robotic-based surgery in such a procedure allows surgeons to remove the target tumors with extreme precision without injuring critical adjacent structures [38].

1.3 Robot Structure and Features

The only two FDA-approved and commercially available robotic systems for surgery are da Vinci and Flex [15, 24]. Neither was approved for skull base surgery; nevertheless, several studies have reported the successful use of the da Vinci machine in certain skull base surgeries [32, 33, 39–42]. To date, there have been no data about implementing the Medrobotics Flex robotic system in skull base surgery because it was only introduced into commercial use after its approval in 2020 [38].

The da Vinci surgical system comprises three components: a surgeon's console, a patient-side cart, and interactive arms [15]. The surgeon's console is typically in the patient's room, and the interactive arms are controlled from there [15, 20, 43]. The number of interactive arms varies according to the system model [15, 20]. They are used to grasp objects, dissect, cut into tissues, take sutures, apply clips, and perform different tasks with conventional surgical instruments, e.g., cautery. One arm controls a three-dimensional camera [15, 20].

The robots used for surgery (particularly endonasal endoscopic transsphenoidal surgery (EETS)) have different features, including their technique, interface, safety characteristics, tools for control, set-up time, and operative time [32]. The technique can be two- or four-handed depending on the size of the adenoma. The four-handed technique is preferred for large ademonas [38]. It entails meticulous collaboration between at least two surgeons [32]. One surgeon is responsible for holding the endoscope while the second performs the surgical dissections [32]. In long and complex procedures, this collaboration is usually challenging, particularly when rapid coordination is required to optimize the fixed visualization of the surgical field and the maneuverability of several surgical instruments in long narrow corridors [32]. Hybrid solutions have been provided to overcome this problem [44]. An endoscopic holder was developed, attached to the robotic system and controlled via a foot pedal. However, there are few data about their effectiveness because they have only been introduced recently [32].

The interface of the robot can be either cooperative or by telemanipulation [41, 45]. The collaborative approach requires the surgeon to hold and move the endoscope, as in conventional non-robotic surgery, but the robot maintains the position of the endoscope when the surgeon leaves it [45]. In the telemanipulation mode, the surgeon can control the endoscope's position via a joystick, foot pedal, voice, or head movement [41].

Many safety features have been incorporated into the robots to prevent accidental injury to vital neurovascular structures during procedures [32]. The most common of these features are an integrated 3D navigation system, loss of control mode, forced thresholds, vocal commands, and the ability to change the robot's orientation

[32]. The set-up and operative time also differ among robots, ranging from approximately 2 minutes to up to 30 minutes [45].

Robotics for skull base drilling have been described in the literature [25]. The most common are the computer-assisted design/computer-automated manufacturing (CAD/CAM) skull base drill [46], the replica study drill [47], and the drill described by Dillon et al. [48] These drills have given promising results, but none of them has been FDA approved to date [25].

1.4 Approaches to Robotic Skull Base Surgery

Skull base surgery is mainly carried out to excise neoplastic and non-neoplastic tumors or lesions originating at the anterior, middle, or posterior cranial fossae to minimize brain manipulation [49]. Each fossa requires specific surgical approaches for access, e.g., fronto-orbital and extended orbital approaches for anterior fossa lesions (e.g., congenital craniofacial malformations such as craniopharyngioma, meningioma, fibrous dysplasia, pituitary adenoma), and sellar, parasellar, petroclival, and lateral temporal approaches for middle and posterior cranial fossae lesions (such as meningioma and trigeminal ganglion schwannoma) [34].

Incorporating robotics into skull base surgery involves different approaches [42]. Not all the approaches used in conventional endoscopic skull base surgery, mentioned above, are used. Robotic surgery involves either single orifice approaches (transoral or endonasal) or multi-orifice approaches (combined transoral-transnasal, combined transantral-transnasal, or combined transcervical).

1.4.1 Endonasal Endoscopic Approach

The endonasal endoscopic approach (EEA) is the preferred choice in most skull base surgeries; endonasal endoscopic transsphenoidal surgery (EETS) has become the main technique for pituitary and sellar tumors because it is minimally invasive [38]. Less common EEAs include suprasellar, petroclival, and infratemporal approaches [50].

Several limitations have been reported in the use of robots in the EEA for skull base surgery. The commercially available endoscope provides 2D visualization of the surgical field; depth perception is critically important during surgery [50]. The ergonomics of robot use in the EEA are unfavorable because bimanual surgery requires the four-hand technique, the limitations of which have been described [31]. A third limitation is that the robots available commercially, e.g., the da Vinci system, were not designed to perform skull base operations. Their long and rigid structure precludes flexibility of motion and dissection into the tissues [51].

Successful experiments on 80 cadavers determined the characteristics of the EETS pathway and workspace for robotic design and development [52]. In addition, a navigator system with multi-information integrated tactics for surgery (MINITS) (Fig. 1.1), providing not only anatomical images but also the trajectories under a QR

Fig. 1.1 The illustration shows the application of MINITS

code, is included for tracking the anticipated directions for neurosurgeons [53]. This is essential.

On the other hand, the robots allow 7 degrees of freedom and 90 degrees of articulation, which is not the case in endoscopic surgery, so the surgeon can reach narrow areas without tremor [54]. They are also superior to endoscopic surgeries in that they can suture the dura without the risk of cerebrospinal fluid leakage [50].

1.4.2 Transoral Surgery

Transoral surgery (TORS) is one of the most common approaches in robotic surgery, especially in the head and neck, to access the oropharynx, hypopharynx, and glottic region [55]. Since 1985 it has been proven capable of accessing structures from the fourth cervical vertebra to the sphenoid sinus caudally [56]. However, no attempts to use TORS in neurosurgery to reach the sella turcica were made prior to 2018, when Chauvet and Hans [31], in their three-stage study, used TORS on eight cadavers, computed tomography (CT) of 36 skulls, and 7 patients. They attempted to place the da Vinci machine behind the hard palate to face superiorly, unlike the conventional inferior-facing placement in head and neck surgeries [31]. Their findings showed that their innovative TORS held promise for reaching the sella region and pituitary tumors.

Not only was TORS successful in removing cystic pituitary tumors, but it was also shown by Malley et al. [40] to be capable of reaching the parapharyngeal space and infratemporal fossa and removing cystic neoplasms from those regions.

The TORS approach was reported to have several advantages over the widely adopted transsphenoidal approach. The side effects, especially rhinological, were minimal [31]. It allowed the surgical field to be visualized in 3D, not just 2D. The maneuverability of the surgical instruments was excellent, even in narrow spaces. There is growing evidence that TORS could be advantageous in handling pituitary tumors with large suprasellar extensions. However, the da Vinci system still has the disadvantage of being limited to cystic tumors [31]. Solid masses cannot be removed adequately even if they are well-visualized and reachable [31].

1.4.3 Transoral Robotic Surgery (TORS) Combined with Extended Endonasal Approach (EEA-TORS)

TORS combined with the Extended Endonasal Approach (EEA-TORS) was described by Carrau et al. [57] in 2013. They performed the technique initially on cadavers, then applied it to two patients, one with chondroma of the clivus extending to the second cervical vertebra, the other with a nasopharyngeal adenoid cystic fibroma extending to the infratemporal fossa and the hard palate [57]. The combined approach gave excellent results; successful total resection of both tumors with almost no complications and good postoperative recovery [57]. The advantage of the combined technique is improved visualization of the nasopharynx, infratemporal fossa, and the posterior skull below the eustachian tube level, which are not reachable by EETS. However, its success depends largely on the high level of experience of the surgeons performing the procedures, given the limitations of the robotics used.

1.4.4 Other Approaches

Other approaches for accessing the skull base via robots have been reported, such as the combined transantral-transnasal approach and combined transcervical approach, through which the authors successfully accessed the anterior fossa and sellar regions in several cadavers. However, this approach has not been attempted on patients to date [42].

1.5 Advantages

Compared to conventional endoscopic surgery, robotics has several advantages in skull base surgery [38]. It allows more detailed 3D visualization of the surgical field with a fixed view throughout the surgery, enhancing the accuracy of the procedure [58, 59]. Its considerable versatility enables the surgeon to perform tremor-free surgery, which is of the utmost necessity in narrow spaces with adjacent critical neural and vascular structures, as in skull base surgery [38]. Bimanual surgery is feasible using robots [58, 59]. Furthermore, the ergonomically designed surgeon's console allows the camera and all the instruments to be controlled fully [42].

Moreover, robot-assisted skull base surgery lowers operation times and therefore costs, especially for procedures requiring time-consuming drilling [25]. It reduces postsurgical discomfort and postoperative local complications (e.g., the nasal turbinate), shortens the hospital stay, and accelerates postoperative recovery [40, 60]. The da Vinci system also allows the dura to be sutured, which is not accessible with conventional endoscopic surgery, reducing the rate of infection and enhancing healing [25].

1.6 Limitations and Challenges

Despite the appealing advantages of robots in skull base surgery, several limitations retard their progress in this field. Along with their high cost, none of the commercially available surgical robots is designed to deal with the critical and delicate structures encountered in skull base surgery in such narrow surgical corridors [42]. The robots are large and rigid, making them challenging to handle through narrow spaces [38, 42]. The navigation systems are not fully developed, making tissue manipulation in the visualized surgical field suboptimal. Many other technical limitations still need to be overcome, such as the long set-up time for many machines and the lack of haptic feedback for surgeons. The robots lack the high-speed drills and suction devices crucial in surgical procedures in this region [58, 59]. The learning curve is also relatively slow, and the demands of collaboration in specific techniques (e.g., the four-handed technique) add to the challenge [32].

In addition, the literature provides few data about their efficacy and safety. Most studies have been performed on cadavers and a small number of patients with various conditions and in different centers with different levels of experience in neurosurgery [60]. Robots have proved effective only for cystic and soft pathologies; many skull base masses arise from rigid bony structures [25].

1.7 Conclusions

The use of robotics in skull base surgery is evolving, and robots have been reported to improve many of the limitations of conventional endoscopic surgery. Even though many advances are still required in software and structural development before robot use can be implemented in regular clinical practice, neurosurgeons should consider the advantages and disadvantages of robotic-assisted skull base surgery. Their decisions should be based on comparing the pros and cons of this technique to the conventional endoscopic approach in relation to each individual patient.

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