# The Future of Robotics in Skull Base Surgery

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## 10.1 Introduction

Although robotics are typically associated with STEM fields today, the word robot actually originated from a play written by Karel Capek, which was first performed in 1921 [1]. The Czech word *robota* translates to slave labor, and the play, *Rossum's Universal Robots*, told the story of robot servants performing tedious tasks for humans and the revolution that followed [2]. Despite early descriptions of robots in the arts, it was not until decades later that robots became scientifically realized [1] with the invention of the Unimate, the first industrial robot. After at, industrial use of robots grew exponentially, and almost 25 years after the invention of Unimate the PUMA 560 (Westinghouse Electric Corporation, Pittsburgh, PA, USA) became the first surgical robot to be used in 1985 [1].

While definitions of robots vary, primarily because of disagreements regarding whether robots require artificial intelligence and autonomous function, three main types of robotic systems have been identified within the field of surgery [2]. Active systems work autonomously to complete pre-programmed tasks. Semi-autonomous systems use pre-programmed tasks in conjunction with surgeon control. Master-slave systems such as the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA, USA) are operated entirely by the surgeon and are characterized by a complete lack of autonomous function.

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Since the invention of the PUMA 560, major advances have been made in the field of surgical robotics including the landmark development of the da Vinci system. Today, their use has become standard in urological, gynecological, and general surgery [3]. Surgical robotics have been optimized for these fields allowing their use in many procedures to become standard practice. Unfortunately, the bony constraints of the skull base present challenging limitations not seen in the abdomen or pelvis and have made the use of currently available robotic surgical systems difficult in these anatomical regions.

Current research on skull base robotic surgery has mainly used the da Vinci surgical system to compare surgical approaches to the skull base in cadavers and rare clinical studies. While one of the goals of surgical robotics is to allow for minimally invasive procedures, current tools are large in comparison to the preferred entry points to the skull base such as the nostril. As a result, while cadaver models can prove feasibility, they often fail to provide a purely minimally invasive method of approaching the skull base. While research is performed with currently available technology, new robotic surgical systems are in development and offer hope based on features that include the incorporation of haptic feedback and decreased robotic arm size [4, 5].

In addition to the development of novel surgical robotics, research is being conducted on various applications including telesurgery, image guidance systems, and the automation of surgical robots using machine learning models [6]. While much research will be needed prior to clinical adoption of these applications, the many advantages they could provide offer an exciting glimpse into the future of skull base robotic surgery and the field of robotic surgery as a whole.

## 10.2 Current State of Surgical Robotics

One of the first robotic surgical systems to be used and arguably the most popular to date is the da Vinci Surgical System. The introduction of the da Vinci, which features 3D visualization, tremor filtration, and wrist-like movements, marked the beginning of a massive push for adoption of robotic systems in many surgical fields [2]. While tremor filtration increases the degree of precision, 3D visualization and increased degrees of freedom potentially mimic the advantages of open surgical techniques. The degrees of freedom provided by the EndoWrist technology used in the da Vinci system are particularly advantageous because they provide greater maneuverability than conventional endoscopic instruments [7]. While conventional endoscopic instruments provide insertion, rotation, pitch, yaw, and grip for a total of five degrees of freedom, the da Vinci has external arms that provide insertion, pitch, and yaw in addition to the EndoWrists that provide internal pitch, yaw, rotation, and grip, for a total of seven degrees of freedom (Fig. 10.1). However, despite the many potential advantages of surgical robotics, their widespread use has been limited to only a few disciplines: urology, gynecology, and general surgery, with more recent applications in neurosurgery and otolaryngology. That said, the proposed future

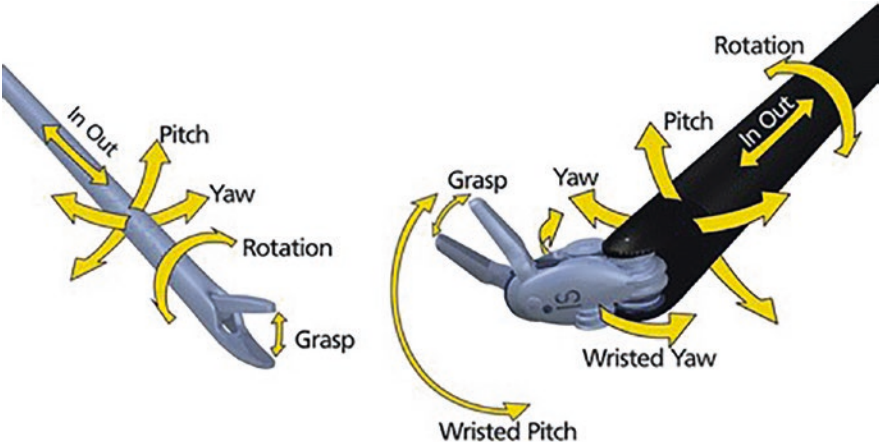

**Fig. 10.1** Comparison of movement capabilities in endoscopic and robotic instrumentation. Conventional endoscopic instruments (left) provide five degrees of freedom while the da Vinci EndoWrist (right) allows for seven degrees of freedom due to the hinged wrist at the working end of the instrument

applications of surgical robotics extend far beyond this list of specialties. Notably, while the EndoWrist has not been approved by the FDA for use in the skull base, the increase in degrees of freedom available will probably be an important design requirement for the development of skull base-specific robotic equipment.

### 10.2.1 Applications of Robotic Surgery in Urological, Gynecological, and General Surgery

Urological, gynecological, and general surgery are currently leaders in the clinical application of robotic surgery. In 2000, the first robot-assisted prostatectomy was performed, followed by formal FDA approval for the procedure 1 year later [8]. Previously, most prostatectomies were performed as open procedures; since then, robotic-assisted prostatectomies have increased dramatically. In fact, robotic-assisted radical prostatectomy increased from 13.6% to 72.6% between 2003 and 2012 [9]. In addition to radical prostatectomy, urological robot-assisted procedures include radical cystectomy and partial nephrectomy [10]. Following a few years behind urological applications of robot-assisted surgical devices, the FDA approved the use of the da Vinci in gynecological surgeries in 2000 [11]. Since then, the da Vinci has become a standard tool in several gynecological procedures such as hysterectomy, myomectomy, oophorectomy, endometriosis treatment, sacrocolpopexy, and tubal anastomosis. Lastly, there is a growing use of surgical robots in general surgery including inguinal and ventral hernia repair and cholecystectomies [12].

### 10.2.2 Applications of Robotic Surgery in Neurosurgery and Otolaryngology

While a few fields have embraced surgical robotics, skull base neurosurgery and otolaryngology have been slower to adopt these new technologies despite the precision that surgical robots could lend to the field in technically difficult and repetitive tasks [13]. Currently, robotics in neurosurgery are primarily used in conjunction with imaging to provide navigation assistance, a technique that has grown in popularity owing to the fragility of structures in the brain and spine. Clinical applications include intracranial biopsy, pedicle screw placement in spinal surgeries, and placement of intracranial leads such as in stereoelectroencephalography and deep brain stimulation. Presently, only two surgical systems are under active use and development in cranial neurosurgery [14]. Neuroarm (IMRIS, Deerfield, MN, USA) uses intraoperative magnetic resonance imaging to provide image guidance during procedures. 3D images of the surgical site, haptic feedback, and the ability of the robotic arms to use microsurgical tools are additional features of the system. One potential drawback is the requirement for intraoperative MRI capabilities, which are absent in many operating rooms. The ROSA System (Zimmer Biomet, Warsaw, IN, USA) also uses image guidance and haptic feedback and has been shown to improve accuracy while minimizing risks. This system allows for pre-operative planning using MRI data and can perform tasks autonomously with surgeon oversight or be directly controlled. In 2021, a study was published on the use of Laser Interstitial Thermal Therapy (LITT) ablation of a posterior fossa mass using a customized 3D implant that highlighted the benefit of a tool such as ROSA for pre-operative planning of LITT procedures on difficult-to-reach masses [15]. One of the largest studies on the use of robotic support in pediatric neurosurgical cases was published in 2017 [16]. In this study, 128 procedures were performed using the ROSA system including electrode implantation for stereoelectroencephalography, stereotactic biopsy, neuroendoscopy, pallidotomy, shunt placement, deep brain stimulation, and stereotactic cyst aspiration. The study outcomes supported the use of the ROSA system owing to its safety and the minimization of postoperative morbidity, with a surgical success rate of 97.7% in the 128 procedures studied and an early clinical transient complication rate of 3.9%. This indicates that the use of ROSA in neurosurgery will probably continue to grow in the coming years.

While neurosurgery has been somewhat slow to adopt robotic systems, otolaryngology, and specifically head and neck, has seen a more rapid increase in the use of robotics since the FDA approved application of the da Vinci for transoral robotic surgery (TORS) in 2009 [5]. Since then, TORS has been investigated for use in several head and neck applications, specifically oropharyngeal, hypopharyngeal, and laryngeal disease through the minimally invasive transoral approach. In fact, TORS has become a widely accepted method for treating oropharyngeal squamous cell carcinoma (SCC) and presents several advantages over alternative treatment options. While TORS has found most success in the treatment of oropharyngeal SCC, application of this method is also under investigation for treating obstructive sleep apnea, thyroid and parathyroid diseases, laryngeal lesions, and sublingual and submandibular gland diseases, and for diagnosing carcinomas with unknown primaries [5, 17].

## 10.3 Current Research on Skull Base Robotic Surgery

While robotic surgery is becoming the standard of care in some specialties because of its enhanced precision and ability to perform procedures with minimally invasive access, skull base surgery has notably lagged. Major obstacles to adoption involve the complex anatomy of the skull base combined with the narrow anatomical corridors of typical access points relative to currently available surgical robotic systems [18]. Current research on robotics in skull base surgery most commonly uses the da Vinci system and investigations primarily involve approaches to the skull base in cadaver and limited human studies to explore the advantages, limitations, and areas of need in skull base robotic surgery.

### 10.3.1 Advantages and Limitations of Robotics in Skull Base Surgery

While the limitations of currently available technology have restricted the clinical feasibility of skull base robotic surgery, robotics in this setting has many potential advantages. As the most popular system, the da Vinci will serve as the main robotic system for analyzing the advantages and limitations of robotics in skull base surgery.

The da Vinci system provides 3D visualization, seven degrees of freedom, and tremor filtration in addition to enhancing surgical ergonomics [18, 19]. Altogether, robotics in surgery provides the potential for minimally invasive procedures that could improve patient health and cosmetic outcomes. The increased precision provided by the excellent visualization, maneuverability, and tremor filtration of surgical robotics has the potential to increase the safety of such procedures and could obviate the need for many commonly performed open procedures in the future.

While the potential advantages of robotic skull base surgery are exciting and promising, numerous limitations will need to be addressed in next generation surgical robotics before they can be realized clinically. Additionally, a cost-benefit analysis will be needed to determine whether the cost of the surgical robotics, training, and maintenance is outweighed by enhanced patient outcomes and safety.

As previously stated, the da Vinci system was not originally created for application in the skull base. As a result, several major limitations will need to be addressed in future iterations of novel surgical robotic systems before minimally invasive robotic skull base surgery can be adopted clinically. Systematic reviews of the current state of research in robotic skull base surgery have revealed a number of these key limitations [18–20]. Perhaps most problematic is the size of the da Vinci arms, which are markedly larger than those used in standard endoscopic endonasal procedures. While standard endoscopes are 4 mm in diameter, EndoWrist instrumentation is currently available in 5 mm and 8 mm sizes [21, 22]. This difference has made it incredibly challenging to find a suitable approach to the skull base that remains minimally invasive. Another limitation is the lack of a drill in currently available da Vinci systems. Drills are frequently used in skull base operations, and without incorporation of such a tool these procedures require all drilling to be performed bedside by a second surgeon. A third limitation is the lack of haptic feedback in the da Vinci system. While the visualization provided by surgical robotics is excellent, work on the skull base with its complex and delicate structures would benefit significantly from tactile feedback, which is not currently available. Until such feedback is readily incorporated, delicate work around critical neurovascular structures is likely to be deemed unsafe by most skull base surgeons.

## 10.3.2 Robotic Approaches to the Skull Base

Currently, skull base robotics is limited by access through the nostrils with available instrumentation. As such, accessory ports have been described, primarily through cadaveric dissection. The feasibility of robotic-assisted endoscopic surgery of the skull base was first studied in 2007 using a transantral approach on four cadavers to access the central and anterior skull base in order to ensure proper closure of dural defects [23]. Since then, several studies have been published exploring novel approaches to the skull base in an attempt to realize the many potential advantages of robotic surgery that have been largely limited in this anatomical region to date. Below we will review some of the primary approaches to skull base robotics by access technique.

### 10.3.2.1 Transnasal Approach

Most research on robotics in skull base surgery has used the da Vinci system with alternative approaches to the skull base. Although the da Vinci is widely available, with several design advantages, the diameter of the arms along with restrictions on maneuverability within the relatively small nasal cavity make it unsuitable for a pure transnasal approach to the skull base [20]. Therefore, although a transnasal approach to the skull base is theoretically appealing, very little research has been done on this approach using robotics. One proposed solution is to use the Flex System (Medrobotics, Raynham, MA, USA) [24], which enables compatible flexible instruments of only 3.5 mm diameter to be used and provides visualization using an endoscope with an HD camera system and 180 degrees of flexibility. Notably, the Flex System also provides haptic feedback to the surgeon, which is currently unavailable in the da Vinci system.

While the study of pure transnasal access successfully explored the potential for the Flex System in skull base pathology, the method involved partial removal of the septum and midfacial degloving on four cadavers (Fig. 10.2), so it is not ideal for

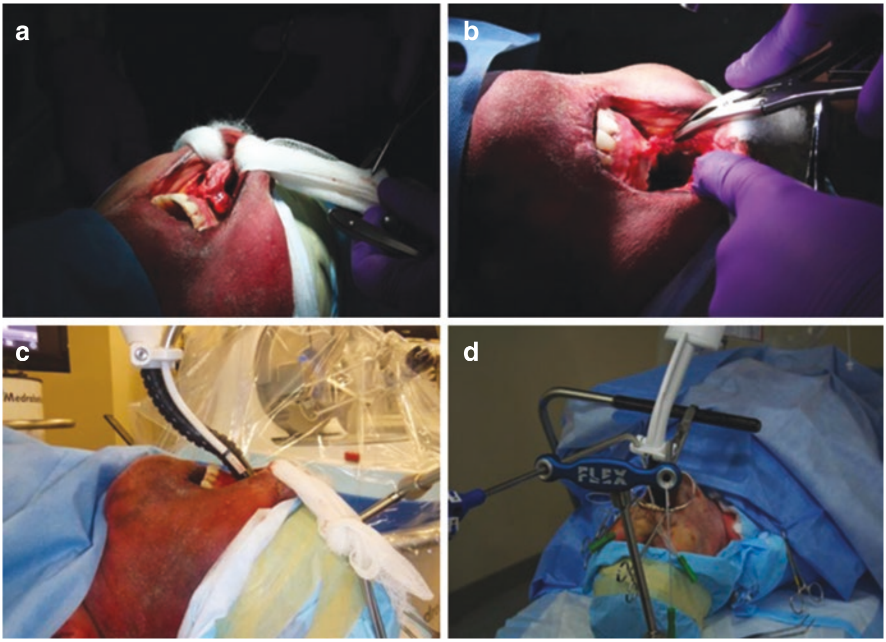

**Fig. 10.2** Flex Robot access through midface degloving approach. Although a transnasal route would theoretically provide the ideal access to the skull base, current systems are too bulky to work within the confines of the nostrils. Additional access options include a modified midfacial degloving and b resection of parts of the maxillary frontal recess and nasal septum with bilateral medial turbinectomy. After surgical preparation for transnasal access, c endoscopic endonasal visualization is employed followed by d introduction of compatible flexible instruments to the skull base

clinical use [24]. Future research will be needed to create less invasive procedures using the Flex System for a pure transnasal approach to be feasible.

#### 10.3.2.2 Transoral Approach

Among the currently researched approaches, transoral is among the most prevalent [19]. The aperture being much wider than the nose, a combined transoral approach can accommodate larger instruments while maintaining the desired minimally invasive techniques with no incisions additional to alternative approaches. Early transoral approaches used transpalatal incisions to increase visualization in several cadaver and human studies [25–27]. However, with decreases in the size of the da Vinci arms, a transoral approach without palatal incisions has also become feasible [20] (Fig. 10.3). In fact, in 2016, Chauvet et al. became the first group to report on the clinical use of a purely transoral robotic approach for removing sellar tumors in four patients [28]. However, a major limitation of the transoral approach is that access is largely limited to the nasopharynx, sphenoid, and sella.

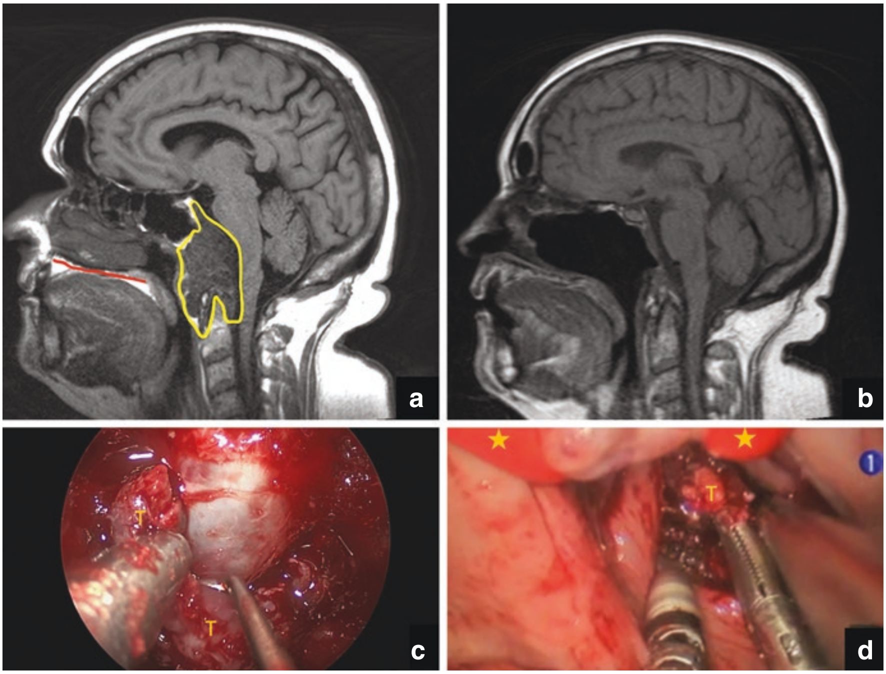

**Fig. 10.3** Transoral Robotic-assisted Nasopharyngectomy for clival chordoma. (**a**) The chordoma (outlined in yellow) involves the entirety of the clivus and into C1 and the retropharyngeal space. The hard palate (outlined in red) creates a bony limit to inferior extension with conventional endoscopic instruments. (**b**) MRI after removal of the chordoma via a transoral approach. (**c**) Endoscopic Endonasal Approach allowed for the tumor to be peeled from the pre-pontine dura, but could not access the most inferior portion of the tumor. (**d**) Transoral Assistance with the da Vinci enabled the remaining tumor to be removed because of articulating instrumentation (T = Tumor; * = red rubber catheter retracting the soft palate)

### 10.3.2.3 Supraorbital and Transorbital Approaches

The supraorbital keyhole approach is a minimally invasive technique for accessing the skull base. While the small incisions are beneficial for patients, they limit instrument movement and visualization for the surgeon, including the added difficulty of working around the supraorbital nerve. Robot surgical systems have been proposed as a way to mitigate these limitations [29, 30]. While greater dexterity has been achieved for the supraorbital keyhole approach using the da Vinci surgical system, conflicting opinions regarding safety and feasibility remain. One large limitation remains the narrow access point that prohibits the simultaneous use of endoscope and instruments. This makes it likely that adoption of this method will require novel surgical robotics better suited to the narrow access points used in skull base operations.

An alternative solution has been investigated in a study that involved both transorbital and transnasal access to the skull base [31]. This approach was used to avoid some of the space limitations encountered in singular methods of approach and resulted in an increased range of angles between instruments. This study was performed using computer simulation, dry skulls, and cadaver models; further investigations will be required to determine the clinical feasibility and safety of this approach.

#### 10.3.2.4 Transantral Approach

A few studies have also been performed using cadaver models to prove the feasibility of transantral approaches to the skull base using the da Vinci. A major potential advantage of robotics in the skull base is the potential for suture closure of dural defects through minimally invasive surgeries [32]. In 2011, Kupferman et al. used a bilateral transmaxillary approach to repair dural defects successfully in four fresh frozen cadaveric heads using robotic-assisted techniques. This approach enabled the anterior skull base to be reconstructed. Two years later, Blanco and Boahene studied approaches to both the anterior skull base and the infratemporal area [33]. The anterior skull base was accessed using transmaxillary and nasal corridor approaches in combination. While the approach was successful, researchers noted that the size of the da Vinci arms placed limitations on maneuverability even after surgical expansion of the nasal corridor. Altogether, while a transantral approach to the skull base is feasible, redesigned surgical robotics will be necessary to optimize the approach and will include distal articulating tips and miniaturization of the robot arms to enhance use in skull base regions.

#### 10.3.2.5 Transcervical Approach

Transcervical approaches have been tested with some success in combination with transoral or transnasal cameras [34]. They provide an excellent range of motion and instrument maneuverability. In the transcervical approach, trocars are inserted close to the angle of the mandible though a paramandibular incision, while the optic lens is inserted either transorally or transnasally. Unfortunately, the lack of a drilling tool in the da Vinci system remains a major hindrance to this and other techniques to access the skull base. Dallan et al. have also investigated transcervical approaches to the skull base [35]. In this study, combined transcervical-transnasal access was achieved and was determined to be superior to transcervical-transoral approaches for dissection of the posterior skull base in cadaveric models on the basis of enhanced visualization. Despite increases in range of motion and maneuverability, no clinical cases have been reported to date.

## 10.4 Envisioning the Future of Robotic Surgery

The potential advantages of robotic surgery have made adoption of new technology in operating rooms promising for surgeons, patients, and innovators. As some of Intuitive Surgical's (Sunnyvale, CA, USA) restrictive patents have begun to expire and new technologies become available, we are likely to see a shift in the surgical robotic system market. Already, many new systems are being developed and are preparing to undergo the process of FDA approval. Additionally, new technology in other sectors including augmented reality and artificial intelligence has begun to be incorporated into surgical systems. While technologies such as telesurgery and programmed robotic surgeries were once considered science fiction, current research suggests that these applications of robotics will become feasible in the foreseeable future.

## 10.4.1 Novel Surgical Robotic Systems

Currently available surgical robotics have revolutionized surgery over the past two decades. That said, remaining areas of need include incorporation of haptic feedback and drilling instrumentation, reduction in cost and surgical arm size, increased flexibility, and further studies proving the benefits of surgical robotics in relation to their cost. Up to this point, the da Vinci surgical system has championed the surgical robotic market. However, over the last decade or so, novel robotic systems have been in development across the world and are potential competitors in the market. Several of these newer surgical robotics will be described in what follows, chosen primarily on the basis of their potential for direct use in skull base surgery or for specific desired features in these surgeries (Table 10.1).

### 10.4.1.1 Flex Robotic System

The Flex Robotic System is currently used in head and neck surgery and was approved by the FDA in 2015 after being developed specifically for use in TORS procedures [5]. Unlike some robotic systems, the Flex system was designed as a

**Table 10.1** Comparison of surgical robotic systems with regard to application in the skull base

| Robotic system | Advantage | Disadvantage |
|---|---|---|
| da Vinci | Seven degrees of freedom, 3D visualization, tremor filtration | Cost, lack of haptic feedback, relatively large instrumentation, lack of drill |
| Flex | Haptic feedback, rigid and flexible camera state options, lower cost, smaller instrumentation, compatible flexible instrumentation, increased access | Requires 3D goggles, optics less sharp than da Vinci, hybrid system uses manually controlled instrumentation rather than robotics |
| Senhance | Eye tracking, haptic feedback, reusable easily moved instruments | Bulky equipment, lack of articulating instruments |
| Versius | Five-wristed robotic arms, haptic feedback, lower cost | No FDA approval, limited current applications |
| REVO-I | Comparable design to the da Vinci at lower cost | No FDA approval, limited current applications, less experience |
| SPORT | Multi-articulated instruments, single port design increases accessibility | Currently in research and development phase |
| Concentric tube robot | Design optimized to size constraints and bony anatomy increasing MIS accessibility, size, flexibility, and maneuverability ideal for skull base | Currently in research and development phase |

hybrid system with a flexible robotic endoscope and manually controlled instrumentation. Some of its advantages over the da Vinci include incorporation of haptic feedback, the option of either rigid or flexible states, increased access thanks to smaller instrumentation, and lower cost. Although originally designed for use in head and neck surgery, the device has since been used in general surgery and gynecology, further proving the benefit attainable from more flexible robotic designs that address the access and line of sight problems that limit many current robotic systems [36]. While the Flex system requires 3D goggles and provides worse optics than the da Vinci, the haptic feedback is a notable advantage for head and neck surgeries [36]. Moreover, the Flex system provides easier access to cancers of the larynx, distal tongue base, and hypopharynx that were previously difficult or impossible to resect using TORS, and it has been shown to be both safe and reliable.

#### 10.4.1.2 Senhance Surgical Robotic System

Two years after the approval of Flex, the Senhance Surgical Robotic System (Asensus Surgical, Durham, NC, USA) received FDA approval in 2017 [4]. While bulky equipment size and lack of articulating instruments mark pain points for this system, the incorporation of eye tracking to control the camera system based on eye focus and head movements make it particularly intriguing. Additional features include incorporation of haptic feedback, seven degrees of freedom in each of three arms mounted on individual carts, and reusable instruments with easy replacement thanks to a magnetic attachment design. Currently, the Senhance system is used primarily in gynecological and colorectal procedures, but applications could expand as research on this system continues [5].

#### 10.4.1.3 Versius Robotic System

The Versius Robotic System (CMR Surgical, Cambridge, United Kingdom), which is currently used in Europe for colorectal, gynecological, renal, and upper GI surgeries, is awaiting FDA approval in the USA [4, 5]. This modular system uses up to five different wristed robotic arms with the incorporation of haptic feedback and compatibility with 5 mm instruments. It is estimated to be more cost-effective than currently commercially available systems, offering hope for continued cost reduction in surgical robotics in the future.

#### 10.4.1.4 REVO-I Surgical Robotic System

In 2015, the South Korean Meere Company introduced the REVO-I surgical robotic system (Meere Company, Hwaseong, Gyeonggi-do Province, South Korea) [37]. This system is similar to the da Vinci and could be a future competitor in the American market pending FDA approval given the similar capabilities combined with reduced cost of the REVO-I system [38]. The REVO-I system is far newer the da Vinci so its applications are currently limited. In Korea, REVO-I has been used primarily for cholecystectomy and a few cases of appendectomy. That said, given the similarities between the two systems, the REVO-I is likely to follow a similar trajectory of expanding surgical applications to the da Vinci as more research is performed.

#### 10.4.1.5 Single Port Orifice Robotic Technology Surgical System

The Single Port Orifice Robotic Technology (SPORT) (Titan Medical, Chapel Hill, NC, USA) is a surgical system currently under development and boasting access-related advantages similar to systems such as the da Vinci SP and the Flex Robotic System, both of which are single port systems [4, 5]. While not yet FDA approved, SPORT has reported success in animal models. The SPORT design consists of a single port 25 mm in size through which two multi-articulated instruments can be inserted.

#### 10.4.1.6 Concentric Tube Robot System

One robotic system of particular interest here is a concentric tube robot that originated in the MED Lab at Vanderbilt University. This device involves curved telescoping tubes that can bend and elongate, featuring movements of needle-sized arms that are described as tentacle-like [39]. This system was built specifically for transnasal robotic skull base surgery so its design is optimized for the size constraints and intricacy of the anatomy involved. In 2015, this technology was used in a phantom study of endonasal skull base tumor removal [40]. Several years later, it was used in a phantom study for transnasal removal of orbital tumors [41]. Both studies proved successful and offer an exciting glimpse into future applications of concentric tube robots in surgery. While designed for transnasal usage for skull base tumors, this technology has the potential for use in many different areas of the body that are currently difficult or impossible to reach with commercially available surgical robotics.

### 10.4.2 Image Guidance and Augmented Reality

Image guidance and the application of augmented reality in surgery have become topics of study and debate over the past decade as technological capabilities improve, but the lack of cost-benefit analyses makes further development and adoption challenging. Notably, a number of studies have been published investigating the value of image guidance and augmented reality in head and neck surgical cases including TORS and cochlear implantation [42–46]. One current limitation of image guidance and augmented reality involves registration, a step that effectively marks areas of the patient (typically using bony landmarks or surface anatomy) so the computer can track them and display instrumentation and 3D overlays properly. Unfortunately, intraoperative shift of tissue is not uncommon and can result in inaccuracies in image guidance and augmented reality applications [47]. To address this problem, research is being performed to develop a deformable registration algorithm using cone beam computed tomography (CBCT) [45]. This research was performed in TORS of the tongue base and showed the feasibility of the technique and the advantages of augmentation, which included relevant vasculature and desired resection data. While further study of registration accuracy will be required, this marks an important step toward implementing image guidance and augmented reality technology in head and neck procedures. Another relevant study showed the feasibility of incorporating augmented reality into cochlear implantation procedures using the da Vinci in a cadaveric model [44]. Although much research will be required to develop and ensure its accuracy and safety, this technology has the potential to improve patient outcomes and change medical education in surgery.

### 10.4.3 Telesurgery

The origin of the da Vinci system and surgical robotics as we know them today actually stemmed from the desire to implement remote surgical procedures on military personnel and astronauts [2]. Accordingly, early versions of this technology received heavy funding from NASA. Telesurgery involves the remote control of master-slave robotic systems. In principle, these surgeries could be performed from extremely remote locations provided the set-up is established appropriately on site. This was tested for the first time in 2001 by a team in New York, USA on a patient in Strasbourg, France [48]. Unfortunately, several limitations including latency time, lack of haptic feedback, cost, cybersecurity threats, equipment acquisition, and legal/billing issues and public skepticism have severely restricted the clinical application of telesurgery since then [48, 49]. That said, several potential advantages of telesurgery are worth considering. These include the elimination of long-distance travel, providing healthcare to medically underserved populations, encouraging surgical collaborations, and addressing surgeon shortages [49]. With advances in network speeds, development of haptic feedback in surgical robots, and new robotics entering the market, potentially reducing cost, there is hope that we can take advantage of these benefits more fully in the coming decades, ensuring a future in which safe, minimally invasive, surgical care is trusted and widely available. That said, the push for robotic automation could make telesurgery irrelevant in the future as active robotic systems are improved and commercialized, potentially reducing the need for long distance control of master-slave systems.

### 10.4.4 Surgical Robotic Automation

The development and application of machine learning models and automation have increased enormously over the past 10 years. However, while autonomous robots grow in popularity and use, the feasibility of implementing them in surgery remains uncertain. Industrial automation requires the creation of robots that perform repetitive, predictable tasks. Such robots do not require the incorporation of machine learning models. In contrast, surgical robotics will require the ability to sense and respond to novel situations appropriately, thereby requiring the development of machine learning models for these applications. This ambitious goal will require careful consideration of surgical skills and the methods that can be used to analyze them, improved understanding of the safety and reliability of autonomous systems, and a thorough understanding of how robots adapt to new challenges [50]. Beyond the technical issues presented by the development of autonomous surgical robotics, researchers, and innovators should be prepared to address problems and thus gain acceptance and trust from the public as well as physicians. Despite the many current limitations and areas of research, machine learning offers exciting opportunities for the future of surgical robotics.

Currently, a few robotic surgical systems are programmable or aid in surgical decision-making including CyberKnife (Accuray, Sunnyvale, CA, USA), Mako SmartRobotics (Stryker, Kalamazoo, MI, USA), and Yomi (Neocis, Miami, FL, USA) [51]. CyberKnife uses real-time imaging during treatment to concentrate radiation at the site of the lesion while reducing the extent of injury to healthy tissue and adjusting for slight movements throughout the procedure [52]. Mako SmartRobotics is currently used for total knee, total hip, and partial knee replacements [53]. It involves precision surgical planning based on patient scans that reduce resection of healthy tissue and provides a data analytics component for comparing outcomes and identifying areas of improvement. Lastly, Yomi is used in dentistry for procedure planning and uses augmented anatomical visualization and haptic feedback [54]. These are just a few surgical robotics that have begun the process of incorporating real-time patient-specific data into decision-making and serve as the basis for surgical robotic innovation and automation in the future. While current technology offers more limited results than the promises of fully autonomous systems, these systems serve as proof of concept for the feasibility and benefits that can be achieved in the future. Ultimately, the goal of machine learning models in surgical robotics is to train the robots to perform a vast library of surgical skills competently, thus enabling the robot to complete surgical procedures from start to finish with minimal or no intervention from surgeons. While initial surgical robotics will be developed as semi-autonomous and involve skills and eventually procedures that are repetitive and fairly predictable, robots will eventually gain both autonomy and complexity through the use of machine learning [50].

## 10.5 The Idealized Skull Base Robotic Surgery

Robotic surgery has undergone remarkable advances over the past two decades since the FDA approval of the da Vinci in 2001. Although there is currently no ideal surgical robotic system for use in the skull base, increased adoption of robotic surgical systems, increased development of novel systems, and further development of current systems promise a bright future for skull base robotic surgery. While the development of such a system will take time, many of the key features are already in research and development stages. The first and most obvious feature required for adoption of skull base robotic surgical procedures will be enhanced and miniaturized instrumentation. The Concentric Tube Robot System [39] is one example of a technology that could be applied to an ideal system given its potential for addressing problems of small access points and bony constraints and allowing for a purely transnasal approach. Another feature of an ideal system will include the seven degrees of freedom for instruments, which provides much of the benefit of current robotic systems. Tremor filtration and 3D visualization are also important features to maintain with additional instrumentation including drills, Doppler, and nerve stimulators. Seamless integration with operative navigation will allow radiographic reference to the instrument's location to be made at all times. Haptic feedback will be another crucial feature given the delicate bony drilling performed in skull base surgery and will serve to increase the safety and precision of these procedures. Another feature that could increase safety and precision is the use of augmented reality to create digital 3D overlays of key neurovascular structures to assist with surgeon identification. Other ideal features would include telesurgery capabilities and eventually robotic automation, facilitating access to these surgical techniques for which there is inadequate training in different areas of the world or a potential shortage of surgeons. Lastly, the cost of an ideal system such as the one described, and of robotic surgical systems more generally, could benefit from significant reduction. Currently, there are major concerns regarding the cost of acquisition, maintenance, and training regarding the da Vinci and other surgical robotic systems [55]. While further analysis of the costs and benefits of robotic surgery compared to traditional approaches could mitigate some of these concerns, overall reduction in the cost of these systems will enable their use to be more easily justified and ultimately allow for clinical realization of their many potential benefits.

## 10.6 Conclusion

Currently, clinical use of robotics in skull base surgery is incredibly limited. However, with exciting new developments in surgical robotics and related technology, the potential benefits and applications cannot be overstated. While the da Vinci is currently the leading robotic surgical system, major limitations including size and lack of haptic feedback have not allowed for clinical adoption in many specialties. Through research into several approaches to the skull base using the da Vinci and other surgical robotic systems, these limitations have been thoroughly explored and clearly require either advances over the current design or novel robotic systems built specifically for the skull base. Since several of Intuitive Surgical's patents are expiring and research has shown the need for advances in robotics, we are likely to continue to see the development and approval of surgical robotic systems. Judging from the current technology and rapidly evolving research interests, it is likely we will see the integration of robotics into skull base surgery in the near future. Some advances that will make this possible include incorporation of haptic feedback, miniaturization of instruments, and flexible instrument and scope options that will increase access. In addition to addressing the limitations identified, future advances are likely to include applications such as telesurgery, image guidance, and surgical robotic automation. Although ambitious, these advances will enable skull base surgeries to be performed in a minimally invasive manner, potentially ensuring shorter recovery time, better outcomes, and enhanced precision while also preparing for a future in which robots can perform surgeries remotely and autonomously for safe, widely available care.

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