Robotics for Approaches to the Anterior Cranial Fossa

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5.1 Historical and Current Methods in Anterior Cranial Fossa Approaches

Depending on the pathology within the anterior cranial fossa, classic surgical approaches can be classified into two broad categories: open, versus minimal access or minimally invasive. Historically, open approaches, usually relying on access via midfacial approaches, bicoronal craniotomies for subfrontal or interhemispheric approaches, pterional, or orbitozygomatic, were often employed to access structures within the anterior cranial fossa. Pathologies addressed in this way include skull

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M. M. Al-Salihi et al. (eds.), *Robotics in Skull-Base Surgery*,
https://doi.org/10.1007/978-3-031-38376-2_5

base tumors (e.g., meningiomas and sellar tumors) and carcinomas, anterior circle of Willis aneurysms, anterior encephaloceles, and facial, orbital and/or anterior skull base fractures [1–10]. Morales-Valero et al. offered a comprehensive historical overview focusing on the use of craniotomies for anterior cranial fossa meningiomas [11]. Although open approaches are still used in specific cases, minimal access approaches relying on surgical microscopes, endoscopes, and/or exoscopes have grown in popularity during the 50 years since they were introduced.

Minimal access approaches in anterior cranial fossa operations are not new to neurosurgery and skull base surgery; the first transsphenoidal approach to remove a pituitary tumor was performed in 1907 by Dr. Hermann Schloffer via a superior nasal route through a transfacial lateral rhinotomy incision [12]. However, the introduction of the operating microscope to neurosurgery by Dr. Theodore Kurze during the late 1950s meant such minimal access approaches could be undertaken more confidently, so the technique was adopted swiftly [13]. Further improvements to microscope design by neurosurgeons including Dr. Gazi Yaşargil meant greater mobility and ease of visualization during microscopic surgery [13–15].

The first transsphenoidal approach to a pituitary tumor using a microscope was conducted in 1962 by Dr. Jules Hardy [16]. Further adoption/development of techniques such as endonasal endoscopy for anterior skull base surgery made it easier to see inside the tight cavities, as needed for minimally invasive access to the anterior cranial fossa [17]. The value of endonasal endoscopy for resection of pituitary tumors via a transsphenoidal approach was first demonstrated in 1977 [18]. The pure endonasal endoscopic approach to pituitary lesions was first adopted at the Universities of Toronto and Pittsburgh in 1996 while others were using the endoscope as a mere adjunct to the microscope for transnasal procedures [19, 20]. Another minimal access approach to the anterior cranial fossa made possible by the endoscope and/or intraoperative microscope is the endoscopic-assisted supraorbital keyhole approach [21–26]. This has been used for resecting meningiomas within the anterior cranial fossa and for treating aneurysms [22, 27].

Currently, an extended endonasal endoscopic approach for access to the anterior cranial fossa is preferred when feasible. Numerous studies have compared endoscopic and microscopic surgeries for tumor resections in the anterior cranial fossa, and the data suggest that endoscopic surgeries provide superior outcomes such as gross total resection or postoperative meningitis rates in functioning versus nonfunctioning pituitary adenomas [28–32]. Endoscopic transsphenoidal approaches have also proved superior to transcranial approaches for resecting tuberculum sellae meningiomas even with optic canal invasion [2]. Minimal access techniques for access to the anterior cranial fossa have benefits over craniotomy-based approaches. These include minimal retraction and manipulation of the brain with accompanying neurovascular structures and increased visualization of the surrounding anatomy [33–35]. Although the benefits of endoscopic and microscopic techniques are tremendous, there are many drawbacks. First, numerous studies report the ergonomic difficulties associated with operating tools such as endoscopes and their potential musculoskeletal effects on surgeons [36, 37]. Additionally, the rigidity of endoscopes often makes it difficult to navigate the regional anatomy of the cranium, paranasal sinuses, and nasal cavities with limited 2D fields of view secondary to the limited degrees of freedom of the endoscope [34]. The endoscopic approach also requires a specific training curve in the anatomy laboratory [38, 39]. Surgical instruments used for minimal access approaches are often limited by their rigidity, making tasks such as suturing, hemostasis, and retraction difficult within such confined spaces. Many of the drawbacks associated with both microscopic and endoscopic techniques have to an extent been addressed by the relatively recent development of surgical exoscopes for neurosurgical use [40]. The literature documents a wide spectrum of exoscope uses, ranging from educational purposes in cadaver labs to tumor resection and implantation of vagus nerve stimulators [41–44]. Specific to the anterior cranial fossa, exoscopic approaches have been used to treat dural arteriovenous fistulas, craniopharyngiomas, and pituitary adenomas, and to clip aneurysms, to name just a few pathologies [45–47]. Montemurro et al. comprehensively summarized the current state of exoscope use in both cranial- and spine-based neurosurgery [48]. Continuing advances with exoscopes allowing for improvements in depth-perception and better visualization in narrow surgical corridors will surely allow exoscope use to increase. Needless to say, endoscopic and exoscopic techniques have proved complementary in several scenarios, including anterior and anterolateral skull base craniofacial resections [47].

5.2 Brief Overview of Robotic Skull Base Surgery

Robotic skull base surgery is defined by the surgical robotic type, surgical approach, and anatomical constraints of the trajectory to the lesion. Currently, robotic anterior skull base surgery is in its infancy, with limited applications to patient care. Mostly, it is still being extrapolated from computer modeling and cadaveric approaches to live patients as the robots are being developed to overcome the challenges associated with robotic skull base surgery [49].

Surgical robots for the skull base are classed as passive, semi-active, or active systems. Robots that require the surgeon’s input to direct and maneuver them are passive systems. They are also described as surgically assistive robots and include robots that act as instrument holders. Semi-active systems provide robotic guidance to the surgeon, for example, mechanical guidance with drilling. Active system robots function autonomously and carry out surgical tasks independently as they receive information from their environment [50–52].

Active systems are subclassified into supervisor-controlled, tele-surgical, or shared control. In supervisor-controlled systems, the robot automatically performs a surgical task while the surgeon supervises it. Tele-surgical active systems are controlled by the surgeon in real time via haptic feedback. Shared-control active systems give full control to the surgeon as the robot provides steady manipulation of instruments [50–52]. Another broad classification of robotic anterior skull base systems is true surgical robots versus experimental robots; i.e., those ready for patient care versus cadaver laboratory use [50–56].

5.3 Robotic Surgical Approaches to the Anterior Skull Base

The ultimate goals of robotic anterior skull base surgery are to limit brain retraction, provide more direct exposure and access to pathological lesions, decrease neurovascular manipulation, improve visualization, and limit morbidity/mortality while improving patient outcomes [34]. These approaches also provide improved ergonomics for the surgeon, reducing surgeon fatigue and musculoskeletal injuries [34, 57, 58]. Below, we have divided these approaches into single versus multi-portal/combined methods, each category further subdivided on the basis of anatomical approach.

5.3.1 Single Portal

5.3.1.1 Transoral Robotic Surgery

Transoral robotic surgery (TORS) was the initial robotic approach to lesions of the oropharynx and nasopharynx. This was adapted by Lee and colleagues in 2010 for skull base lesions [59] (Fig. 5.1).

They used three arms of the da Vinci Surgical System Robot (Intuitive Surgical; Sunnyvale, California, USA) for TORS skull base approaches on seven cadavers. The cadaver heads were positioned supine with a Crowe-Davis retractor (Storz; Heidelberg, Germany) inserted into the oral cavity [59]. The approach required retraction of the soft palate after two rubber catheters were inserted through the nose, brought out laterally through the mouth and then clamped in position. With the da Vinci robot (Intuitive Surgical; Sunnyvale, California, USA) at the head of the table, its three arms were angled and placed in the mouth while avoiding buccal compression. One arm held either an 8.5-mm diameter 0° or 30° angled endoscope placed through the mouth in the midline. The other two arms held 5 mm diameter articulating EndoWrist instruments placed transorally. A midline incision along the

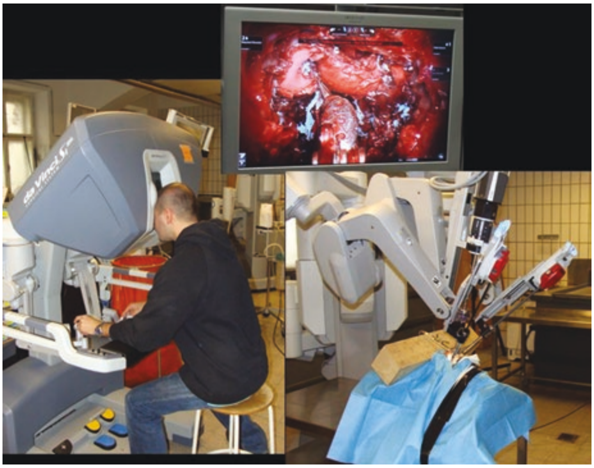

Fig. 5.1 Author Antonio Di Ieva's anatomy demonstration of using the da Vinci robot for a transoral approach to the anterior and middle skull base (Centre for Anatomy and Cell Biology, Department of Systematic Anatomy, Medical University of Vienna, Vienna, Austria, 2011)

posterior pharyngeal mucosa was made by the surgeon controlling the robot from the console. The assistant surgeon stood beside the head to assist and monitor clearance of the robotic arms. The clivus, foramen magnum, and eustachian tubes were identified. Once the bone was identified following soft tissue dissection, the assistant surgeon used a matchstick burr (AM-8) for drilling. After the clivus was identified, a sphenoidectomy was performed. The 30° endoscope was angled cephalad to allow the sella, tuberculum sellae, and planum sphenoidale to be visualized. However, the robotic arms were at their maximum extension at this point and could not angle more cephalad owing to the restrictions of the oral aperture [53, 59]. Despite this disadvantage, Chauvet and colleagues successfully performed TORS for resecting sellar tumors in 2016, with some modifications to the above approach [60]. They prospectively selected four patients to undergo TORS for resection of a sellar tumor with suprasellar and cystic components using three arms of the da Vinci Si robot (Intuitive Surgical; Sunnyvale, California, USA). All patients had an oral aperture of at least 38 mm. Successful TORS requires a normal oral aperture generally ranging from 38.9 mm to 45 mm [34]. With an endotracheal tube in the left labial commissure and robotic arms at the head of the patient, an 8.5-mm 30° endoscope was inserted into the mouth behind the posterior edge of the hard palate to identify the cavum landmarks, choanae, and posterior nasal septum superiorly and eustachian tubes laterally. EndoWrist instruments (5 mm) in the two arms were introduced into the mouth and used to dissect a U-shaped flap along the hard palate, which was then positioned along the right choana for the sphenoidal approach. The key point defined as the junction between the vomer and sphenoid was identified and the robotic arms were removed to allow for drilling, but the endoscopic arm was left in place. The sphenoid sinus was opened inferiorly and expanded with a combination of drilling, robotic arm instruments, and Kerrison rongeurs. The dura was opened with a flexible fiber CO_2 laser (Lumenis Be Ltd., Yokneam, Israel) along with robotic instruments. The tumor was resected, and a mucosal flap was replaced [60].

The literature describes few complications associated with TORS for anterior skull base surgery, probably because only a limited number of surgical procedures have been performed on patients. As with any intradural anterior skull base procedure, there is an inherent risk for cerebrospinal fluid (CSF) leakage [60]. Additionally, there is a hypothetical risk for velopharyngeal or velopalatine insufficiency owing to scar contracture, and a risk of oronasal fistula formation; however, neither of these has been reported in the literature for robotic anterior skull base surgery [51, 60]. More benign postoperative risks associated with TORS include dysphagia, temporomandibular joint pain, delayed otitis media, and sore throat [61, 62].

Despite the successful use of TORS to access the anterior skull base and sellar/parasellar regions, significant limitations to this single port approach limit its generalizability. Patients without normal oral apertures are not amenable to this procedure. The steep angles of the anterior skull base make the da Vinci robotic arms difficult to maneuver cephalad to gain further anterior access to the anterior skull base. Cadaveric and clinical studies have demonstrated that an endonasal endoscopic approach complementing TORS allows for improved visibility in areas such as the infratemporal fossa, nasopharynx, clivus, and craniovertebral junction [63]. Finally, this is not a strictly robotic procedure because an assistant is required at the bedside to assist with some tasks such as drilling.

5.3.1.2 Robotic Surgery

The endoscopic endonasal approach has become the workhorse for neurosurgical minimal access to the anterior skull base and sellar/parasellar regions. Despite this, the transition to a direct robotic endonasal approach has been difficult because the restrictions of nostril diameter and angle lead to a narrow funnel effect [52]. A pure transnasal approach with the Medrobotic Flex system (Medrobotics Corp.; Raynham, Massachusetts, USA) was described by Schuler and colleagues in 2015 [64]. This system is a surgeon-controlled flexible robotic endoscope with a high-definition camera and six LED light sources at the tip providing 3D working space and flexibility of up to 180° (Figs. 5.2, 5.3, and 5.4).

There are two working channels on either side of the endoscope allowing for delivery of instruments and triangulation of tools in the working space. The diameter at the tip is 15x17 mm and the maximum distance the endoscope can travel is 17 cm. Owing to the restrictions of nostril diameter, partial midface degloving, and partial nasal septectomy were needed to allow the Flex Systems endoscope to be placed in the nasal cavity [64].

Although adequate visualization of the sinus system and skull base is feasible, this procedure is invasive as it requires partial midfacial degloving and, potentially, piriform ostetomies. Binasal approaches could be feasible, but computer modeling demonstrates that the optimal angle between two robotic tools transnasally at the skull base is at least 20°; however, the current working angle with the da Vinci robot (Intuitive Surgical; Sunnyvale, California, USA) is only 14.7°. Therefore, this approach is best used with a combined transorbital or transmaxillary approach [34, 65]. Novel robotic endoscope holders have also been employed in transnasal approaches for pituitary pathologies, the goal being to reduce the physical strain on

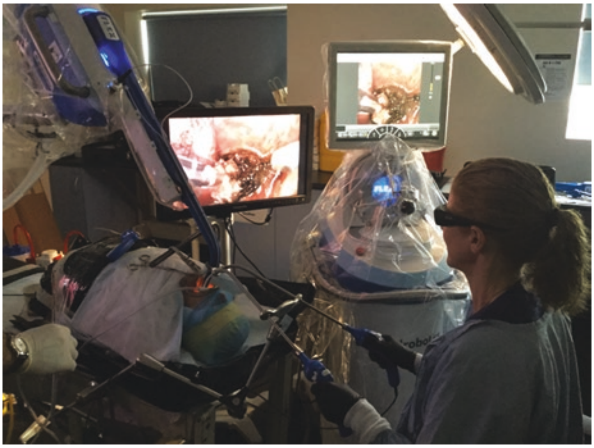

Fig. 5.2 Author Raewyn Campbell shows a transoral approach to the skull base using the Medrobotics Flex robot (Medrobotics Corp.; Raynham, Massachusetts, USA), demonstrating the position of the surgeon and favorable ergonomic posture

Fig. 5.3 Demonstration of the transnasal approach to the skull base using the Medrobotics Flex robot (Medrobotics Corp.; Raynham, Massachusetts, USA). A modified Weber Ferguson incision was required, and the bony piriform aperture was drilled to access the full nasal cavity and skull base

Fig. 5.4 Another option for positioning using the Medrobotic Flex robot (Medrobotics Corp.; Raynham, Massachusetts, USA) transnasally

surgeons while freeing up an additional hand for them [50, 66]. However, as mentioned above, the limitations of space remain.

5.3.1.3 Transorbital/Supraorbital Robotic Approaches

The robotic supraorbital keyhole approach to the anterior skull base using the da Vinci robot (Intuitive Surgical; Sunnyvale, California, USA) has only been described in cadavers [67]. The robot was positioned 30° relative to the body on the right side of the head, which was secured in 10–15° of extension. After a supraorbital craniotomy, a 0° and 30° upward-facing stereoscopic endoscope was placed through the keyhole to visualize the anatomy prior to the placement of the da Vinci robotic arms. Self-retaining retractors with brain ribbons were used. The surgeon remained at the non-sterile robotic console throughout the procedure. The dura was opened with robotic curved scissors and the right frontal lobe was retracted with a self-retaining snake retractor. Brain relaxation was achieved by CSF release. The optico-carotid cistern was opened with the robotic arm, allowing the optic nerve, optic chiasm, internal carotid artery, and oculomotor nerve to be visualized. An EndoWrist suction/irrigator along with Potts scissors was used to open the Sylvian fissure. The authors could navigate the deep narrow corridor, and after the M1 segment was incised, three sutures were placed relatively quickly and easily to close the defect.

The chiasmatic cistern was then approached and opened using the robot. The 0° endoscope was used to visualize the sellar region. EndoWrist instruments were advanced into the pre-chiasmatic space and the pituitary stalk, gland, tuberculum sellae, and contralateral internal carotid artery were identified. The lamina terminalis was opened, the anterior cerebral artery was dissected to the junction of the A1 and A2 segments, and the recurrent artery of Heubner was identified. The origins of the posterior communicating and anterior choroidal arteries were also visualized. Robotic tools could not perform clip ligation at this point, so a manual clip applier was used to place an aneurysm clip [67].

This mono-portal approach is not uncontroversial. Marcus and colleagues described the da Vinci system's instruments and cameras as overly large, unable to provide adequate visualization, and unsafe for a 25-mm keyhole craniotomy [68]. Therefore, the supraorbital approach could be best as a combined approach with multiple portals. The development of more fine-tuned tools with smaller footprints could make the transorbital approach more feasible, as demonstrated by Faulkner and colleagues in their cadaveric feasibility study using the Versius surgical system (CMR Surgical; Cambridge, UK) [69].

5.3.2 Multi-Portal/Combined Approaches

5.3.2.1 Cervical Transoral Robotic Surgery

To circumvent the limitation of oral aperture size, which leads to a narrow angle for robotic arm access and limits the number of robotic arms accessing the anterior skull base to two or three, cervical transoral robotic surgery (C-TORS) was developed [55]. This combined approach makes it possible to achieve robotic access to the skull base from the cribriform plate and fovea ethmoidalis to the sellar and parasellar regions, clivus, infratemporal and pterygopalatine fossae, and the nasopharynx. O'Malley first described C-TORS approaches in cadavers in 2007 [55]. Using the da Vinci robot (Intuitive Surgical; Sunnyvale, California, USA), a 3D camera was placed transorally. A 3-mm incision was made bilaterally along the posterior border of the submandibular gland. Plastic introducers and round-tip dilators were passed blindly in a circular motion until the camera visualized them intraorally. Injury was avoided by tenting the oral mucosa at the lateral hypopharyngeal region by the round tip dilators and then inspecting the transparent mucosa to determine whether critical structures were trapped by the introducer tip. The mucosa was incised by monopolar cautery. Metal trocars were then placed in the field to admit the passage of 5 mm instruments. To verify that no neurovascular and airway structures had been injured during introducer and trocar passage, the cadaver neck was opened and visually inspected. The TORS approach was performed as described above. Because the increased angles between the robotic arms meant they were no longer constricted by the oral aperture, the anterior and middle skull base including the sella, parasellar, and suprasellar regions could be visualized thanks to the increased maneuverability of instrumentation [55]. A modification by Dallan and colleagues involved endonasal instead of transoral visualization [70], which also provided access to the posterior skull base.

C-TORS provides adequate access to the anterior skull base but is significantly invasive because the trocars are passed blindly through the neck. While the trocars are being passed, injury to critical structures such as the airway and neurovascular bundles in addition to soft tissue destruction could lead to airway collapse, hematoma formation, compressive edema, and injury to the lower cranial nerves. Also, as with TORS, there is a risk for velopalatine insufficiency. In view of these risks, the C-TORS approach has not advanced beyond the preclinical phase of testing.

5.3.2.2 Suprahyoid-Transoral Robotic Approaches

The suprahyoid-transoral approach was described in cadavers by McCool and colleagues as an alternative to the C-TORS approach [56]. A 2–0 silk suture was used to pull the tongue anteriorly and the palate was retracted with a 10-french red rubber catheter placed transnasally and pulled through the mouth. The cadavers underwent nasal intubation to simulate live operative technique. A 1-cm cannula was inserted via a blunt introducer through a 15-mm midline incision at the level of the hyoid bone. With a finger at the base of the tongue, the cannula was guided blindly to the oropharynx via the vallecula. A bite block was placed in the mouth ipsilateral to the side of dissection. The 30° camera of the da Vinci robot (Intuitive Surgical; Sunnyvale, California, USA) and a second robotic arm were placed transorally on the contralateral side. Soft tissue dissection with incision of the posterior tonsillar pillar proceeded superiorly along the salpingopharyngeal fold 5 mm inferior to the torus tubarius. The superior pharyngeal muscle and lateral aponeurotic sheath of the medial pterygoid were divided. The lingual and inferior alveolar branches of cranial nerve V_3 were identified and dissected superiorly to the foramen ovale and the middle meningeal artery was also identified. Dissection proceeded posteriorly to the jugular foramen, internal jugular vein, and lower cranial nerves (IX–XII). One robotic arm and one camera were placed transorally, minimizing the mobility limitations from the robotic arm angles in approaching the anterior skull base [59].

The risks associated with the suprahyoid-transoral approach include hypoglossal nerve injury. This could be mitigated by placing the trocar in the midline as the hypoglossal nerves are lateral. Pre-epiglottic swelling and supraglottis are other risks that could require long-term intubation or tracheostomy [56, 59].

5.3.2.3 Endonasal Transmaxillary Approach

The combined endonasal transmaxillary approach as an approach to the anterior skull base in four cadavers was first described by Hanna and colleagues in 2007 [54]. They performed bilateral sublabial incisions, and soft tissue flaps were elevated to the level of the infraorbital nerves superiorly and nasal piriform aperture medially. Wide anterior maxillary Caldwell-Luc antrostomies were performed.

Wide middle meatal antrostomies and a posterior nasal septectomy were also performed to allow the three arms of the da Vinci robot (Intuitive Surgical; Sunnyvale, California, USA) to be introduced. The camera arm port with a 5-mm dual channel endoscope and a dual charge-coupled device camera for 3D visualization was placed in the nostril and the right and left surgical arm ports were placed in the respective anterior and middle antrostomies to the nasal cavities. Endoscopic anterior and posterior ethmoidectomies could be performed with or without resection of the superior and middle turbinates. The robotic arms were manipulated to perform a sphenoidectomy and expose the planum sphenoidale and sella turcica. Further anterior skull base dissection was performed to resect the cribriform plate, create a dural opening, and repair the opening with sutures [54].

In 2013, Blanco and colleagues expanded on the combined endonasal transmaxillary approach with the da Vinci robot (Intuitive Surgical; Sunnyvale, California, USA) in response to the constraints of limited nostril diameter [71]. A rhinoplasty-type transcolumellar incision was performed and Lega’s technique was used to make marginal incisions along the anterior and posterior margins of the medial crural cartilage to release the medial crural footplates. This allowed the skin below the transcolumellar incision to be freed from the medial crural cartilages, and also expanded the nostrils while reflecting the nasal tip superiorly to create an increased range in the cranial-caudal plane for the endoscope. The inferior turbinates were outfractured and the nostril was expanded in the horizontal plane by a partial septectomy [71].

Despite expanding the nasal corridor, a separate transmaxillary osteoplastic window was needed for instrument mobilization. With a sublabial incision from the central incisor to the third molar, and partial facial degloving with elevation of the soft tissue of the cheek to the level of the inferior orbital rim, an osteoplastic window was removed while the infraorbital nerve was preserved. Robotic arms were positioned at 30° and the posterior and medial maxillary walls were resected to achieve exposure to the nasal cavity. The osteoplastic transmaxillary window enabled up to four 5-mm instruments to be placed in the operative field without obscuring visualization or impairing the mobility of the robotic arms. In the infratemporal fossa, the maxillary and middle meningeal arteries, cranial nerves V_2 and V_3, lateral pterygoid, foramen rotundum, and foramen ovale were identified. Anterior skull base dissection could be performed with access to the posterior ethmoid, sphenoid, sella turcica, and suprasellar and parasellar regions. Stereotactic navigation to verify surgical position involved a Medtronic AxIEM emitter (Medtronic; Minneapolis, Minnesota, USA) and the da Vinci Tilpro interfaced with it. A pedicle septal flap was sutured by the robot to close the anterior skull base defect [71].

Despite the greater access to the anterior skull base, this combined approach is invasive. The endonasal transmaxillary approach requires a significant expansion of the nasal corridor and does not provide access to the anterior ethmoid bone or middle meatus [71].

5.3.2.4 Transcranial Robotic Approach

The ROSA—Robotic Stereotactic System (Zimmer Biomet; Warsaw, Indiana, USA)—is a computer-controlled robotic arm used for stereotactic frameless surgery. It has built-in system software used to implant brain electrodes and for laser interstitial thermal therapy (LITT), catheter placement, frameless stereotactic biopsy, and endoscopic third ventriculostomies [72–75]. After the trajectory to the lesion is planned, the patient is positioned in a Mayfield head holder fixed to the ROSA. The fixed orientation of the head allows for precise robotic stereotaxy. The registration is semiautomated and built into the ROSA system. It uses a laser at the end of the robotic arm to scan the patients' facial contours and relate them to prior 3D high-definition CT or MRI volumetric images. The arm can either be automatically driven or manually adjusted along the axis of the trajectory to achieve a comfortable working distance. Miller and colleagues described the placement of depth electrodes using the ROSA system in eleven pediatric patients with no major complications, and performing biopsy and/or LITT on six patients [72]. Two patients had lesions in the anterior cranial fossa that the ROSA robot accessed for biopsy, stereo-EEG, and LITT. A similar robotic stereotactic system is the RONNA G3 system, which has been used clinically for precise localization during brain biopsy [76].

5.4 Limitations of Robotic Surgery in the Anterior Cranial Fossa

Robotic anterior skull base surgery is limited not only by the complex anatomy and steep angles of the anterior skull base but also by the robotic devices and instrumentation available. The narrow funnel effect, being the minimum angle required between robotic tools to allow for function, is a limitation that currently available robots find difficult to overcome. Bly and colleagues used computer modeling and Artificial Intelligence (AI) tools to analyze the approach trajectories, angles between robotic tools, and distances to skull base lesions in cadavers [65]. These were then tested using the da Vinci robot (Intuitive Surgical; Sunnyvale, California, USA) and Raven robotic systems (BioRobotics Laboratory; Seattle, Washington, USA). They identified increased collisions between robotic arms when the portals were close to each other. Additionally, steep approach vectors to the anterior skull base limited the use of robotic surgical portals. The addition of more portals improved the funnel effect and also improved robotic arm maneuverability.

Robotic arm and instrument size limit maneuverability through working portals [34]. This makes robotic surgery technically feasible in cadaveric studies but potentially unsafe in the clinical setting. Current robots cannot drill autonomously and provide limited haptic feedback. Finally, there is a significant lack of instruments with an intraoperative navigation component for anterior skull base surgery in currently developed robots [77]. This will need to be addressed in future iterations of robots to provide the surgeon with accurate navigation to skull base lesions.

5.5 Future Directions

Robotic surgery, particularly for anterior skull base surgery, has made major strides since its original adoption. However, many advances are still needed for robotic approaches to become as commonplace as endoscope-based techniques. Many of the improvements outlined below relate to robotic surgery generally while others are more specific to neurosurgery.

1. *Miniaturization of Instruments and Increased Instrument Flexibility:* One major pitfall in adopting robotic platforms for use in the anterior skull base has been the size and rigidity of available instruments [34, 65]. This becomes obvious when we consider that many currently employed instruments were not originally intended for use in the small cavities/passageways common in neurosurgery, especially skull base surgery. Thus, one of the biggest advances in the adoption of robotic platforms for anterior skull base surgery would be to create tailored instruments that are small and flexible to operate within a confined environment. A perfect example is the development of concentric tube robots that specifically address the narrow confines of skull base surgery [78]. Extended use of surgical trocars [79] and synergistic collaboration between surgeons and engineers aimed at merging micro-technologies with surgical robotics [80] and improving robot design will eventually lay the foundations for a stepwise advance in the use of robots in skull base surgery [81].
2. *Drilling Capabilities:* In conjunction with the points discussed above regarding the development of new instruments, current robotic platforms also lack drilling capabilities because they do not have the necessary tools or the distal robotic arm strength to stabilize drilling through thick bone. Current TORS performed for anterior cranial fossa access relies on handheld drills [60]. Studies are underway to develop drilling instruments that have simultaneous force feedback [82, 83].
3. *Suturing Capabilities:* Although the adoption of robotic surgery in the confines of skull base surgery allows for more instrument articulation during suturing than endoscopic/microscopic-based techniques, suturing capabilities can still be improved. The most obvious improvement would be force-feedback capabilities, allowing for more fine-tuned handling of the delicate sutures often employed, for example, in vascular procedures [84]. However, the potential for semi- or even full automation of suturing using specialized instruments is more interesting. Many publications have assessed the ability to automate this process in both laparoscopic and robotic surgeries [85–87]. Novel needle-grasping tools have also been developed for adaptation to current robotic surgical platforms [86, 87].
4. *Haptic Feedback:* One of the major drawbacks of any present-day robotic surgical system is the lack of haptic feedback to guide surgeons in the intraoperative manipulation of tissue or other materials [88]. The delicate nature of nerves and blood vessels in anterior skull base surgery means that haptic feedback will be pivotal if safe operations such as tumor resection (regardless of stiffness) or aneurysm clipping are to be performed [89–91]. The utility and feasibility of

incorporating such feedback have been investigated, and it is under development for use in next-generation robotic platforms [92].

5. *Integration of Intraoperative Navigation:* Neurosurgery and skull base surgery, more than any other surgical sub-specialty, depend on a deep understanding of anatomy and on intraoperative imaging navigation to ensure accurate localization [93]. Real-time imaging navigation has many applications, ranging from stereotactic neurosurgery to tumor margin determination and aneurysm clipping [93, 94]. Incorporating real-time instrument navigation with robotic platforms would truly be groundbreaking, and its feasibility has been demonstrated for skull base surgery in cadavers [95]. Newer technology relying on electromagnetic fields for instrument detection promises great adaptability with techniques such as TORS, since no direct line of sight is needed for navigation, and instrument footprint is minimal [96].
6. *Employing Artificial Intelligence:* Recent developments in machine learning have allowed computer vision to be applied to surgery, the computer being able to interpret operative images or video reliably [97, 98]. Computer vision promises the real-time ability to predict important regional anatomy and the next steps in an operation, and even to distinguish healthy from tumor tissue when brain and skull base tumors are to be resected [99–103]. Incorporating such a tool into robotic platforms, and even augmented reality, could provide for a seamless operating experience tailored to each operation and surgeon.
7. *Improving Affordability:* Needless to say, robotic operating platforms have yet to become affordable. System costs are often in the millions of dollars, not including annual maintenance fees or instrument costs [104]. Therefore, access to surgical robotic systems remains limited for many institutions. As more platforms are developed and robotics spread more widely around the world, costs will eventually decrease.
8. *Improving Platform Ergonomics:* Current robotic operating platforms occupy significant space within operating rooms. Also, they often require personnel familiar with the systems to help with setup and management [104, 105]. There is therefore room for improvement in the design of special operating rooms to accommodate robotic systems, and even the design of the systems themselves, ultimately allowing for small footprints and greater ease of use for hospital staff interacting with the modules.
9. *Tele-Surgery Applications:* As robotic surgical platforms are adopted, the ability for providers to perform tele-surgery has become a reality. The first remote operation was a laparoscopic cholecystectomy performed in 2001, with an uncomplicated recovery by the patient [106]. Unfortunately, applications in neurosurgery have remained extremely limited [107]. Tele-robotic spinal surgery of the thoracic/lumbar spine has been demonstrated in the literature [108]. A feasibility study examining tele-surgical removal of a phantom pituitary tumor in a cadaver demonstrated minimal video latency over the 800-km distance and no observable differences for the surgeon performing the task locally and then remotely [109]. Tele-intervention has also been adopted in percutaneous coronary intervention and could perhaps be extrapolated to treating strokes, as demonstrated in

preclinical models by Britz et al. [110–112]. Improvements in network technology, e.g., widespread adoption of 5G, and network security, e.g., blockchain-based frameworks, could allow for more seamless integration of tele-surgical practices [113].

5.6 Conclusions

Robotic platforms for operating on anterior cranial fossa pathologies remain in their infancy. Although several robotic platforms and anatomical approaches have been shown to be feasible at various levels, there has been minimal extrapolation to clinical settings. However, as with any new surgical technique, the development of more refined tools promises greater applicability. More importantly, the eventual adoption of robotic approaches to the anterior cranial fossa promises greater operative ease and potentially better patient outcomes, akin to the leaps accompanying the first adoption of microsurgical or endoscopic approaches in neurosurgery and skull base surgery.

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