Robotic Skull Base Surgery

Mitchell Heuermann, MD[a], Alex P. Michael, MD[b], Dana L. Crosby, MD, MPH[a,*]

KEYWORDS

• Skull base • Sinonasal • Robotic surgery • Robotic skull base
• Transoral robotic surgery

KEY POINTS

- Robotic surgery has made an important impact in head and neck surgery, although its use in skull base surgery has been limited.
- Current approaches to the anterior and central skull base remain fundamentally limited by robotic systems that were never designed to navigate the intricate, delicate anatomy of the skull base.
- New robotic technology is in development to address the current technical limitations of existing robotic systems.
- Cost, safety, and clinical outcomes need to be factored into the indications for usage of robotics in skull base surgery.

INTRODUCTION

Robotic surgery has had a significant impact on multiple surgical specialties and has gained wide usage since the introduction of the da Vinci robotic system (Intuitive Surgical, Sunnyvale, CA) in the early 2000s.[1] Head and neck surgeons have adopted it for use in transoral robotic surgery (TORS) of the oropharynx, hypopharynx,[2] and approaches have also been described for laryngectomy,[3,4] parapharyngeal space tumors,[5] thyroidectomy,[6,7] and neck dissections.[8] Compared with open procedures, TORS procedures promote less-invasive surgical approaches, better visualization of critical structures,[9] and faster operating times.[10] TORS has also been shown to result in better postoperative swallow function,[11] faster recovery, higher rate of margin negativity, and shorter hospital stays[12] than open procedures. Similarly, robotic thyroid procedures have shown improved postoperative pain, swallow, and cosmesis.[6,7]

Despite early success in other areas of the head and neck, the use of robotics in the anterior and central skull base has been limited to date. Several surgical robots have been repurposed for use in skull base surgery, but none are currently marketed or

[a] Department of Otolaryngology–Head and Neck Surgery, SIU School of Medicine, 720 North Bond Street, Springfield, IL 62702, USA; [b] Division of Neurosurgery, Neuroscience Institute, SIU School of Medicine, PO Box 19638, Springfield, IL 62794-9638, USA
* Corresponding author.
E-mail address: dcrosby53@siumed.edu

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designed specifically for the skull base. This has imposed limitations, largely because of the discrepancy between the size and maneuverability of current robotic instruments and the small confines of the anterior skull base. Nevertheless, several approaches have been investigated in cadaveric and human studies that use current robotic technology. These include pure transoral, transnasal, transantral, and transcervical approaches, and combinations thereof. This article reviews the currently available surgical robot technologies and their role in anterior and middle skull base surgery.

CURRENT ROBOTIC TECHNOLOGY

Surgical Robots

The da Vinci robot has become the prototypical and most widely used surgical robot to date. It was first approved for use in 2000 and acquired Food and Drug Administration approval for otolaryngologic surgery in 2009.[13] It has undergone several iterations since its inception (**Table 1**), and is currently controlled by a separate surgeon console that integrates the movement of four rigid arms, three for active instrumentation and one to hold and maneuver the endoscope. Its most recent iteration, the da Vinci SP, notably allows instrumentation through a single 25-mm port as opposed to independent placement of the arms with previous iterations.

To solve the flexibility issues that the da Vinci system faced, the Flex System (Medrobotics, Raynham, MA) was developed and Food and Drug Administration–approved in 2017 for “access to the oropharynx, hypopharynx, and larynx.”[19] It features two 3-mm flexible instruments on both sides of a flexible endoscope, all of which are capable of three-dimensional movement (**Fig. 1**). The endoscope is controlled robotically, whereas the instruments are controlled manually. Unlike the da Vinci system, the Flex System does have limited haptic feedback, but only displays images in two dimensions.[19] Despite the size reduction, this system is still too large to perform traditional endonasal surgery.

Given the size and functionality limitations of existing surgical robots, experimental systems are in development. The SmartArm (Department of Mechanical Engineering, The University of Tokyo, Tokyo, Japan) was designed specifically for endonasal surgery, particularly suturing at the skull base (**Fig. 2**). This system features haptic feedback, 3-mm flexible working tools with 9° of freedom, and a 4-mm endoscope.[20] Wurm and colleagues[21] developed a fully automated robot, featuring an endoscope, drill capable of speeds up to 40,000 RPM, and two ports for irrigation and suction, all within a single 5-mm arm (**Fig. 3**).[22] A novel robotic system being developed by Vanderbilt University features four robotic arms based on a series of tiny concentric tubes, which allow for greater maneuverability along a nonlinear course, making them better suited for pure endonasal surgery (**Fig. 4**).[23–26] This system features arms measuring 2.32 mm in greatest diameter and instruments measuring up to 1.75 mm in diameter, although at present does not support haptic feedback or wristed instruments.[25] It has even been suggested that the concentric tube arms could be custom made for each patient based on their anatomy.[27]

Surgically Assistive Robots

Surgically assistive robots, although not effectors of the surgery itself, aid the surgeon in one or more aspects of the procedure. In the context of skull base surgery, this is usually in the form of an instrument holder or surgically assistive devices. These include the ROVOT-m (Synaptive Medical Corporation, Toronto, Canada),[28] Endoscope Robot (Medineering Surgical Robots, Munich, Germany),[29–31] SoloAssist

Table 1
The da Vinci system in its various iterations, including year of release, number of arms (including instrumentation and camera), and changes compared with prior iterations

Iteration	Released	Arms	Improvements Over Prior Iteration
Standard	2000	3	4th arm added in 2002[14]
S	2006	4	Improved range of motion; improved docking[15]
Si	2009	4	Higher definition camera; second teaching console; single-site surgery using curved trocars[16]
Xi	2014	4	Slimmer, boom-mounted arms; improved maneuverability and reach; integration with operating tables[17]
X	2017	4	Lower purchase cost; no boom-mounting or operating table integration[17]
SP	2018	4	All instruments operate through single 25-mm port[18]

Data from Refs.[14–18]

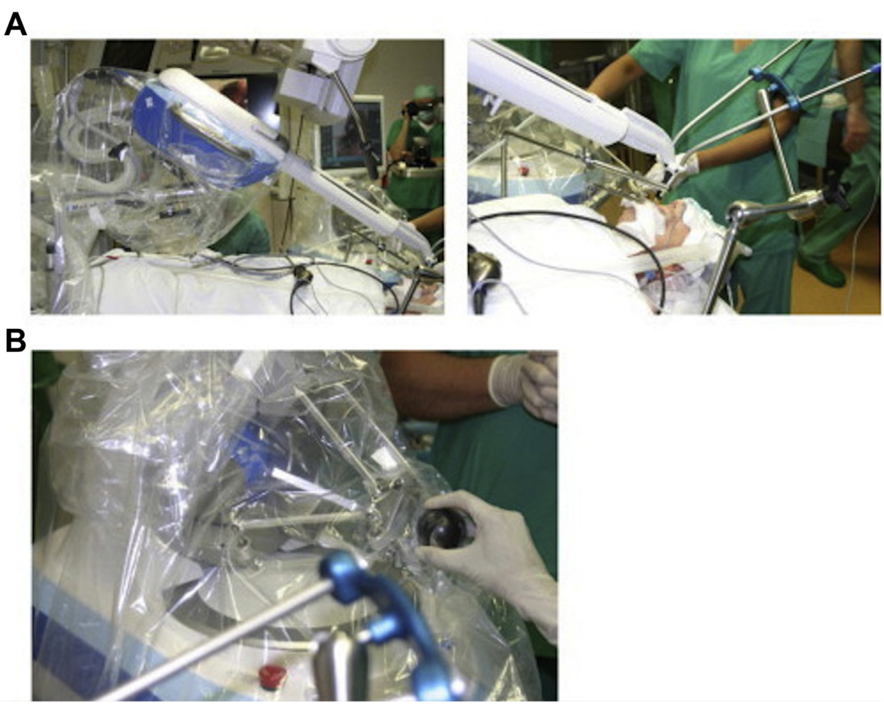

Fig. 1. (*A*) Setup and docking using an integrated flexible robotic endoscope with two flexible instrument arms. (*B*) Control arm for the flexible endoscope. (*Adapted from* Mandapathil M, Duvvuri U, Güldner C, et al. Transoral surgery for oropharyngeal tumors using the Medrobotics® Flex® System – a case report. Int J Surg Case Rep. 2015;10:173-175; with permission.)

Fig. 2. Setup of a novel robot designed for pure transnasal skull base work. (*From* Marinho MM, Harada K, Morita A, et al. SmartArm: Integration and validation of a versatile surgical robotic system for constrained workspaces. Int J Med Robotics Comput Assist Surg. January 2020:e2053; with permission.)

endoscope holder (AKTORmed Robotic Surgery, Barbing, Germany),[32] the now defunct voice-operated or eye movement–operated AESOP system,[33,34] and other experimental assistive robotic systems.[35] Similarly, the iArmS system automatically follows and supports the surgeon's arm during microdissection helping reduce fatigue and enabling more accurate, fluid motion for long-duration cases.[36]

Fig. 3. An example of an integrated robot arm, comprising a drill, endoscope, and two ports for irrigation and suction. (*From* Wurm J, Bumm K, Steinhart H, et al. Entwicklung eines aktiven Robotersystems für die multimodale Chirurgie der Nasennebenhöhlen. HNO. 2005;53(5):446-454; with permission.)

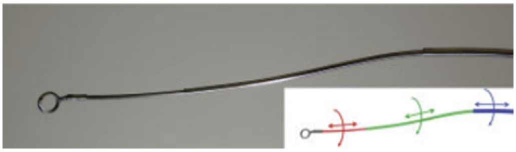

Fig. 4. A representative arm of a concentric tube robot. *Inset image* details the axes of motion for each tube for a three-tube system. (*From* Swaney P, Gilbert H, Webster R, et al. Endonasal Skull Base Tumor Removal Using Concentric Tube Continuum Robots: A Phantom Study. J Neurol Surg B Skull Base. 2014;76(02):145-149; with permission.)

CURRENT SURGICAL APPROACHES

Until recently, most robotic head and neck surgery was limited to use of the da Vinci system. Given the limitations inherent to this system when used for skull base surgery, most studies to date have focused on alternative routes of access for rigid-arm robotic systems.

MULTIORIFICE APPROACHES

The slow adoption of surgical robotics to pure transnasal skull base surgery is likely from smaller diameter of the nostril compared with other natural orifices and design limitation of the da Vinci system that prevent physical interference with the camera and the surgical arms. As such, transnasal access using the da Vinci robot has been limited to a single working endoscopic port while other natural or artificial orifices are used.

Combined Transantral-Transnasal

The feasibility of using surgical robots to access the anterior skull base was first shown in 2007 in a series of four cadaveric specimens.[37] Access was based on bilateral Caldwell-Luc maxillary antrostomies, middle meatal maxillary antrostomies, and posterior septectomy, with placement of the da Vinci arms transantrally and the endoscope transnasally (**Fig. 5**). The authors were then able to surgically access the cribriform plate, planum sphenoidale, sella turcica, and parasellar regions. This approach has been further replicated in other cadaver studies for access to the nasopharynx,[38] sella and cavernous sinus,[39] and infratemporal fossa.[40] To date, there are no reports in the literature using any of these techniques in live patients.

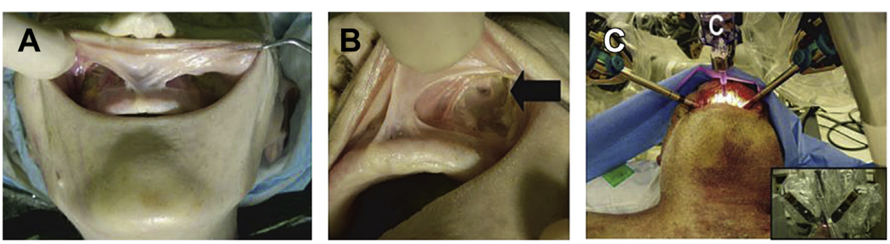

Fig. 5. An example of the transantral approach. (*A*) Bilateral vestibular incisions to expose the anteroinferior maxilla. (*B*) Infraorbital nerve (*black arrow*) relative to surgical field. (*C*) Setup of two robotic instrument arms through maxillary antrostomies and the endoscope transnasally. (*From* Kupferman ME, Hanna E. Robotic Surgery of the Skull Base. Otolaryngol Clin North Am. 2014;47(3):415-423; with permission.)

Combined Transoral-Transnasal

One of the major limitations of pure transoral approaches is the lack of drilling equipment for currently available robotic systems. As such, traditional endonasal instrumentation is often needed to help traverse the bony skull base. This approach has been described in cadaver[41,42] and in live patients for access to the nasopharynx[43,44] and clivus.[42]

Combined Transcervical Approaches

To overcome access limitations of traditional TORS for nasopharyngeal procedures, a group from the University of Pennsylvania described a modified approach (C-TORS) in a cadaver model, in which robotic instrumentation trocars are placed transcervically posterior to the submandibular gland (**Fig. 6**). These terminate in the lateral hypopharynx, and allow access to the nasopharynx, clivus, sphenoid, sella, and anterior fossa.[45,46] Dallan and colleagues[47] described a similar success in a cadaver model with endonasal visualization rather than transoral. McCool and colleagues[48] described a modified approach in a cadaver using two transoral ports and one suprahyoid port for improved access to the infratemporal fossa.

SINGLE-ORIFICE APPROACHES

Transoral

Early pure transoral approaches (**Fig. 7**) to the skull base with the four-arm da Vinci system used a midline or lateral soft palate split for improved access. These have been described in cadaver studies,[49,50] and in several live patients with nasopharyngeal[43,51,52] and infratemporal fossa[53] tumors. By gaining exposure through the hard palate, Ozer and colleagues[54] were able to access the skull base from crista galli to C1. Although splitting the palate dramatically improves surgical access, it carries with it the risk of oronasal fistula formation and scar contracture leading to velopharyngeal insufficiency.[18]

With the reduction in size of the da Vinci arms from 8 mm to 5 mm, cadaver studies have shown the feasibility of nonpalate split transoral approaches to the

Fig. 6. An example setup of C-TORS, with the two working robotic arms placed transcervically just posterior to the submandibular glands (*outlined*), and the endoscope placed transorally. (*From* O'Malley BW, Weinstein GS. Robotic Anterior and Midline Skull Base Surgery: Preclinical Investigations. Int J Radiat Oncol Biol Phys. 2007;69(2):S125-S128; with permission.)

Fig. 7. Setup for a pure transoral approach using one 30° endoscope and two wristed instrument arms. (*From* Newman JG, Kuppersmith RB, O'Malley BW. Robotics and Telesurgery in Otolaryngology. Otolaryngol Clin North Am. 2011;44(6):1317-1331; with permission.)

nasopharynx,[55] sella,[56] infratemporal fossa, and clivus.[46] With the development of the da Vinci SP model, access to the nasopharynx was explored by Tsang and Holsinger with excellent exposure.[18] Nonpalate split approaches have been validated in live patients for access to the infratemporal fossa,[45] sella,[57] and clivus.[58] Access to the nasopharynx using the Flex System has also been demonstrated in cadaver studies,[59,60] although there exist no published studies of its use in live patients.

Transnasal

The transnasal endoscopic approach is currently the preferred method of accessing the anterior skull base, clivus, sella, and parasellar regions. Given the size of currently available robotic systems, published studies on pure transnasal robotic approaches have been comparatively few, limited to a single cadaver study using the Flex System. This approach, however, required partial midface degloving, partial nasal septectomy, and partial removal of the maxillary frontal processes for complete visualization.[61] Nevertheless, this approach allowed access to all paranasal sinuses and wide access to the anterior skull base, sella, clivus, and posterior cranial fossa.

Supraorbital

Hong and colleagues[62] explored the possibility of access to the anterior skull base from above using a supraorbital keyhole craniotomy in a cadaver model, and found adequate exposure and maneuverability for work in the anterior skull base, including suturing. Marcus and colleagues,[63] however, reported conflicting results when a 25-mm keyhole was made and concluded that robotic access was not safe with the da Vinci system because of the bulk of the instruments and camera.

BENEFITS

Compared with endoscopy, robotic-assisted skull base surgery with the da Vinci affords enhanced three-dimensional visualization. This alone may enable improved surgical precision. The da Vinci endowrist allows greater flexibility than what is achieved by the human hand leading to better maneuverability around angled bony structures. Similarly, the enhanced fine motor control of the Da Vinci robotic arms makes suture repair of the dura possible.[36] Robotic surgery can eliminate the issues commonly encountered in traditional four-hand transnasal endoscopic surgery, such as fatigue and tremor. The narrow surgical corridors encountered in endoscopic skull base approaches leads to frequent conflicts between instruments and endoscopes. This may be lessened with alternative robotic approaches with wristed instrumentation. Additionally, the ergonomically designed surgeon's console integrates control of all of the robotic arms, offering the surgeon complete control of the camera and three working instruments. Finally, the newer da Vinci models have the option of using dual consoles, which allows seamless transfer of functions to a second surgeon or allow instruction of a student.[64,65]

LIMITATIONS

Major limitations for incorporation of robotics into skull base surgery still exist. One main drawback is lack of instruments designed for delicate skull base procedures.[64,66] Specifically, the instrumentations included in currently approved devices do not include a drill for skull base bone work.[67] Furthermore, the adoption of surgical robotics to pure transnasal surgery has been limited by the smaller diameter of the nostril compared with other natural orifices, and design limitations of the da Vinci system, which require the surgical arms to be aligned at a minimum of 20° to each other to avoid physical interference with themselves and the camera.[68] Because of these design limitations, a direct approach via a transnasal route is currently impossible. Additionally, the currently available robots do not support integration with image-guidance systems. Lack of haptic feedback for da Vinci instrument contact can prove dangerous, especially when working with delicate structure of the skull base, although this may be offset by exceptional three-dimensional optics afforded by the robot.[64,69] Emerging robotic technologies, such as concentric tube robots, may solve many of these limitations. A cost comparison analysis of robotic head and neck surgery to traditional approaches has not yet been performed, although literature from other specialties generally agree that the cost of robotic surgery is higher because of surgical supply and operating room costs.[70,71] Whether these costs carry with them reduced complication rates, shorter recovery, and improved oncologic control remains to be seen. Furthermore, as with all new technology, there is a significant learning curve especially for surgeons who are otherwise not familiar with robotic technology.[10,72] Adequate training and proficiency before clinical use is paramount to success.

FUTURE DIRECTIONS

With new robotic technologies in development, it is important to develop systems that are safe, versatile, durable, and that provide advantage over traditional surgical approaches. To this end, an ideal robot for use in skull base surgery would be entirely endonasal; be compatible with image guidance; move intuitively with the surgeon's movements; use a self-cleaning endoscope; and allow simultaneous use of multiple instruments that are small, flexible, durable, easily exchangeable, and capable of haptic feedback.[73,74] Clinical trials to date have been limited,[75] but are of paramount importance to show that robotic procedures can be done safely and provide measurable improvement in patient outcomes and quality of life to justify their increased costs. Robotic surgery brings with it the possibility of long-distance telesurgery, although implementation of this has been limited in otolaryngology.[76,77]

SUMMARY

Although TORS has made an important impact in head and neck surgery, robotic skull base surgery is comparatively in its infancy. Although successful access to the anterior skull base has been shown through several approaches, these approaches remain fundamentally limited by systems that were never designed to navigate the intricate, delicate anatomy of the skull base. These limitations are likely to be overcome in the future with the development of specifically designed robotic systems, although cost, safety, and patient outcomes all need to be factored into the indications for their use.

CLINICS CARE POINTS

- No currently available surgical system is approved for use in the skull base
- Several experimental approaches to the skull base with existing surgical robots have been described but are generally not considered to be the current standard of care
- Effective robotic surgery at the anterior and central skull base will likely require new robotic systems or dramatic changes in existing systems
- Novel robotic systems are currently being developed specifically for use in the skull base

DISCLOSURE

The authors have nothing to disclose.

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