Robotics in Pediatric Otolaryngology-Head and Neck Surgery and Advanced Surgical Planning

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KEYWORDS

• Robotics • Pediatric otolaryngology • Surgical planning

KEY POINTS

- Robotic surgery has been successfully applied to many aspects of pediatric otolaryngology.
- Adoption of robotic technology may be improved with advanced computer-aided surgical planning to compare techniques and approaches.
- Advanced surgical planning includes segmentation, virtual reality, three-dimensional printing, optimization algorithms, intraoperative mirror image overlay, and can incorporate robotic instruments.
- Barriers for integration include specialized pediatric instruments as well as time and expertise needed for advanced surgical planning.

INTRODUCTION

Robotic surgery has been explored in pediatric otolaryngology since 2007.[1] Although its applications have been demonstrated in many different areas of pediatric head and neck surgery, its adoption has been limited to larger centers and its reports limited to feasibility studies. Integration of robotic surgery may improve with advanced preoperative surgical planning and newer, smaller robotic instrumentation. Recent advances in computer-aided surgical planning allow for comparison and implementation of different surgical approaches with varying technology including robotics. The ability to surgically access a specific target is a function of visualization, instrumentation, patient-specific anatomy, and morbidity incurred by gaining the access. The two major components that can be optimized include visualization and instrumentation, both

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of which are related to surgical robotics. A major opportunity within pediatric robotic head and neck surgery is to perform the same surgical task but with reduced morbidity incurred to the patient.

CURRENT USE OF ROBOTICS IN PEDIATRIC OTOLARYNGOLOGY

Robotic surgery has been used in pediatric surgery since the initial description of transoral robotic surgery (TORS) in laryngeal cleft repair in 2007.[1] In that case series of 5 pediatric patients, the size of the robotic arms was considered to be a limiting factor for application in the pediatric population as 3 cases could not be completed due to lack of visualization and insufficient space to maneuver instruments.

As TORS technology has advanced, its applications in pediatric head and neck surgery have expanded, including in children undergoing surgery for obstructive sleep apnea.[2–4] A retrospective review of 16 patients between ages 5 and 19 years who underwent lingual tonsillectomy via TORS divided the study population into 3 groups in the order of operation and found that the docking times decreased significantly from the first group to the second 2 groups.[4] Operative time and blood loss were not noted to be statistically different among the groups. The investigators attributed their successful completion of all cases to smaller instruments (5 mm instruments, 12 mm endoscope), unmatched exposure of the tongue base musculature, magnification of working area, and visualization of cranial nerve IX. Another study described 9 patients who underwent base of tongue reduction and lingual tonsillectomy via TORS and stated advantages include a three-dimensional (3D) view and more freedom of motion over endoscopic coblation or radiofrequency ablation.[3] There was one postoperative base of tongue bleed that required intraoperative control and was discharged without further complications.

Another case series described use of TORS in 16 children in a variety of oropharyngeal and airway procedures including resection of base of tongue lesions, resection of supraglottic and hypopharyngeal lesions, and repair of laryngeal clefts.[5] This was the first pediatric case series to describe use of TORS in a variety of procedures in children from as young as 14 days to 15 years. Similar to prior reports, wristed-instrument control, 3D visualization, more precise control of the laser, ability to place more sutures in small spaces, and multilayer closure with greater exposure than in standard endoscopic procedures were identified as advantages. Adequate exposure, obtaining surgical access for robotic arms, and need for a bedside surgeon were noted as limitations. Operative and docking time were not reported due to the large variety of cases, and complications were found to be within expected range for the procedures. It was suggested that specialized airway instruments would likely widen pediatric applications.

Since then TORS has been reported in several case reports for use in pediatric airway reconstruction and head and neck resections.[6,7] It has been used for successful resection of supraglottic neurofibroma with parapharyngeal space extension.[7] In this case, surgeons opted for TORS over transoral laser microsurgery (TLM) due to its superior laryngeal and lateral pharyngeal exposure. However, the patient then required resection of residual disease 2 months postoperatively for which they preferred TLM, as they had adequate exposure with a less cumbersome setup and superior tactile feedback.[7] A laryngeal neurofibroma is shown being resected in **Fig. 1** in a 2-year-old via transoral robotic surgery.

These case series suggest that the known advantages of TORS in adults including increased precision, 3D magnification, tremor reduction, motion downscaling, and freedom of motion superior to that of the human hand[4,7] are also advantaged in pediatric head and surgery. However, the same study also notes that when traditional

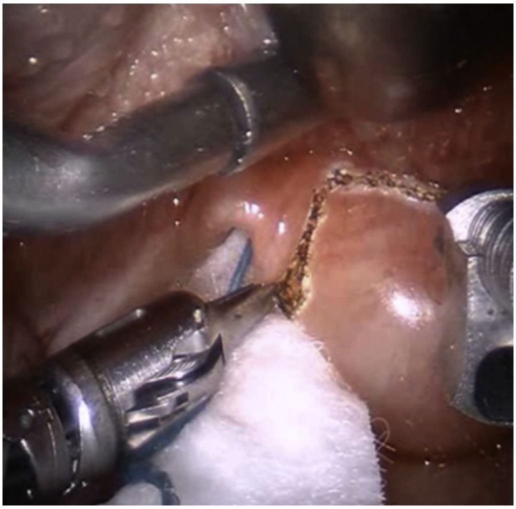

Fig. 1. View of exposure of laryngeal neurofibroma in a 2-year-old resected via TORS.

endoscopic instruments are deemed sufficient during surgical planning, they are preferred due to lack of cumbersome setup and decreased cost.

Most preoperative surgical planning is performed with 2D computed tomography (CT) and MRI combined with the surgeon's experience. Advanced surgical planning can play a role in further adoption of robotic technology, as it could allow for preoperative surgical exploration and comparison of robotic instruments over traditional surgical instruments.

CURRENT ADVANCED SURGICAL PLANNING TOOLS

Preoperative surgical planning provides opportunities for increased patient safety, decreased operative time, and decreased morbidity. Advanced surgical planning refers to the use of technology to enhance the planning process and can include anything from virtual reality to 3D printed models to computer-aided optimization algorithms.

Surgical planning must start with a computer model of the patient-specific anatomy and lesion (Fig. 2). In order to use any of the following methods such as virtual reality, hologram visualization, and 3D printed templates, an accurate model must first be created. To do this, typically cross-sectional imagings (CT and MRI) are used either in isolation or merged to create the anatomic model. For certain anatomic regions, this can be straightforward and automatic segmentation can be used to identify bones and vessels with contrast, but many of the smaller structures within the head and neck still require manual segmentation by an expert. Segmenting cartilage, for example, continues to be a challenge using CT alone.[8] This is time consuming and is one of the barriers for using surgical planning. Once a model is created, depending on the application, simply visualizing the approach (eg, virtual endoscopy) may provide enough insight to the surgeon that he or she now has a better understanding of what the surgical task will entail. In other instances, the surgeon needs more than visualization and requires specific templates or other guides to precisely carry out the surgical task. The topics discussed later are some of the available methods to convey the information from the model to the surgeon regarding patient-specific surgery. As this

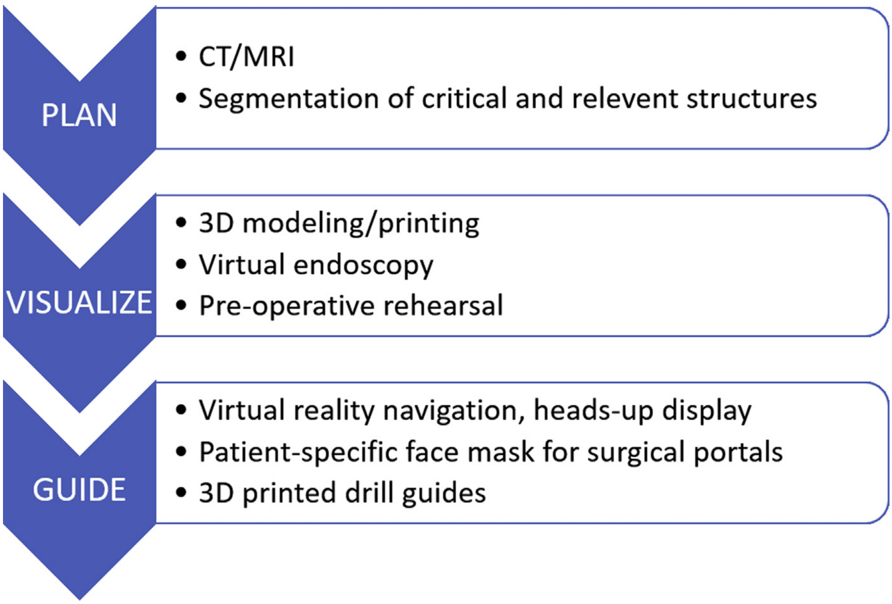

Fig. 2. Stages of advanced surgical planning that can incorporate robotic instrumentation.

process improves, it will be an essential step in adopting new robotic technology to novel surgical approaches.

Virtual Reality

Augmented reality or virtual reality has been well studied in surgical training, and several studies have shown simulation can increase trainee and surgeon confidence.[9] As the patient-specific fidelity and haptic feedback of virtual reality has improved, its use has expanded to preoperative planning. In fact, the benefits of virtual reality surgical rehearsal were shown to improve case selection, selection of surgical tools, and surgical performance in carotid endovascular surgery.[10,11]

With respect to endoscopic skull base surgery, virtual reality can be used to improve surgeon familiarity with important anatomic landmarks with more patient specificity and lower cost than cadaver training. One study created a virtual surgical environment, entitled CardinalSim, and retrospectively reviewed simulation of 10 endoscopic skull base cases.[12] They found excellent correlation in surgical exposure, anatomic features, and location of pathology between the simulation and actual case, suggesting benefits of patient-specific rehearsal before actual surgery. Surgical rehearsal allows surgeons to familiarize themselves with anatomic variations, foresee pitfalls, and adjust operative plans.[12] Several virtual simulators of endoscopic sinus and skull base surgery are available yet their evaluations have been limited to training purposes.[13] However, time and cost needed to manually segment and reconstruct individual patient anatomy from CT scans are major barriers to widespread use in preoperative planning and practice.[13]

In sleep surgery, virtual reality modeled the effects of maxillomandibular advancement.[14,15] Preoperative virtual planning results compared with postsurgical data showed that the simulation reliably predicted facial tissue and anteroposterior airway extension.[14] However, it was not able to accurately predict changes in the lateral velopharyngeal region. Another model guided the surgeon in the extent of maxillomandibular advancement based on goal posterior airway space and tooth-to-lip show in 4 patients.[15] Postoperative posterior airway space and facial aesthetic profile closely matched those predicted by the model.

Virtual reality has also been used to plan and rehearse lateral skull base/otologic surgery.[16–18] Surgical planning via a combination of 3D printing and 3D simulation allowed for avoidance of critical structures in a case study on transcanal endoscopic approach to the petrous apex.[17] Voxelman TempSurg with haptic feedback is a simulation software used for case-specific surgical rehearsal for 24 cadaver temporal bones.[18] Trainee and expert otolaryngologists agreed that knowledge of anatomic variation influenced subsequent surgery on cadaver specimens, particularly the specific boundaries of sigmoid sinus.[18] This study also showed that there was improvement in upload time or time needed to convert a CT scan to a 3D model via segmentation, as surgeons better understood how to use the semiautomatic segmentation process. Surgical planning was rated higher with case-specific data as compared with a generic training model. However, this study still suffered from low fidelity for critical structures such as facial nerve and tegmen.[18] A similar study was conducted in 2 different institutions and also showed that rehearsal increased confidence, which correlated with higher grades on dissection performance.[19]

Despite its complex 3D anatomy, surgical planning for head and neck surgery resection and reconstruction is still mainly done via 2D CTs and MRIs. A recent case series explored the use of virtual reality modeling with patient-specific data before surgery. Surgeons were able to explore the 3D anatomy and practice techniques in cases such as a partial clavicle resection with myocutaneous flap repair and a carotid body tumor. One benefit noted was that the visualization of vascular invasion and intraluminal dimension before surgery—particularly in postradiation cases—could help anticipate operative time and vascular surgery consultation.[20]

Three-Dimensional Printing

3D printing for surgical planning involves the development of a CAD template that is generated from 3D reconstructions from MRI or CT images.[21] Advantages include patient specificity and ability to create single-use models.

3D printed surgical guides have been used in craniofacial surgery to determine the optimal location for internal plates and screws.[20,22,23] Drill and osteotomy guides can be planned and printed in advance to assist the surgeon with regard to optimal orientation, location, and depth. These guides are becoming increasingly accurate and more useful as innovations in transparency and flexibility become available for 3D printing.[24]

In head and neck reconstructive surgery, preoperative simulation with mandibular models were also noted to decrease operative times, as they allowed practice shaping the fibula and fitting it within the mandibular reconstruction plate.[25] Furthermore, cutting guides were 3D printed to allow for cutting and contouring of the fibula bone to fit precisely in segmental mandibular resections defects.[26] Navigation has also been shown to be helpful in planning reconstructions.[27]

A recent systematic review examined the role of 3D printing for the creation of patient-matched surgical guides, templates, and implants in pediatric airway reconstruction.[28] In all cases, preoperative assessment with patient-specific 3D printed models resulted in significant alterations in surgical plans, and expert option was unanimously in favor of using 3D printed models. The use of 3D printed airway models were recommended as a means to reduce complications in complex airway interventions and should be compared with preoperative planning with only 2D and 3D imaging.[28]

NEW DEVELOPMENTS IN ROBOTICS AND ADVANCED SURGICAL PLANNING

Multiobjective Cost Function to Optimize Endoscopic Approach

A multiobjective cost function was recently used to model preoperative planning for skull base surgery.[29] Key skull base structures were segmented using patients' preoperative CT scans. Morbidity costs were assigned to each of the predetermined structures by surgeons, and a weight-based cost function was then used to determine an optimized surgical approach. Resultant pathways were found to be similar to actual approaches performed on patients based on surveys of skull base surgeons when reviewed retrospectively. The algorithm can be expanded to other anatomic regions and potentially be used to optimize approach in many different head and neck surgeries. A major advantage of this method to seek optimized surgical approach is that the boundaries through which instrumentation can function can be defined. As new robotic technology becomes available, the specific surgical pathway through which those instruments need to work can be inputted to identify optimized surgical corridors as a function of lesion location and individual patient anatomy.

A simpler version of this technique can be done without multiobjective cost function optimization, and defines—in great detail—the geometry of the surgical corridor required to perform a specific surgical task (**Fig. 3**).[30] This has been applied for multiple applications to the skull base including the lateral cavernous sinus.[30–32] This permits precise knowledge of the size and shape of surgical corridor, which could enable robotic integration. It could both assess feasibility of current robotic instrumentation but should also be used in the future design of robotic systems.

Mirror Image Overlay

Another method to incorporate surgical planning in guiding the surgeon accurately is the use of mirror image overlay (MIO). This technique can be applied where there is anatomic symmetry. In orbital reconstruction, restoration of the orbital bones to their

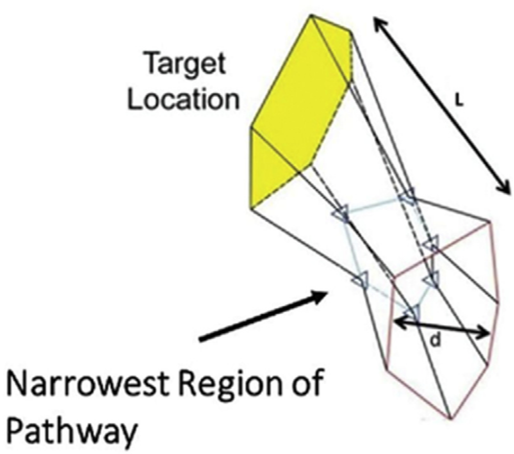

Fig. 3. Mapping of maximal pathway boundaries of potential robotic surgical portal based on the target, entrance, and narrowest region. (*From* Moe KS, Bly RA. Commentary: Comparative Analysis of the Exposure and Surgical Freedom of the Endoscopic Extended Minipterional Craniotomy and the Transorbital Endoscopic Approach to the Anterior and Middle Cranial Fossae. Oper Neurosurg (Hagerstown) 2019;17(2):E47-E49 https://doi.org/10.1093/ons/opy371[published Online First: Epub Date]|.)

correct anatomic position is important to minimize postoperative complications. One advanced surgical planning technique to optimize the orbital bone placement is MIO.[33] This involves duplicating the contralateral (nontraumatized) orbitozygomatic region, reversing (side-to-side) the segment, and superimposing its skeleton onto the fractured, displaced orbit. When combined with intraoperative navigation, MIO can be used to guide a surgical implant into proper anatomic position and has been studied in several cohorts.[33–35]

In another study focused on treating delayed orbitozygomatic fracture with severe enophthalmos, in addition to intraoperative MIO, a model with MIO was 3D printed so that titanium mesh and plates could be prebent on the model.[36] Adequate zygomatic reduction was achieved in 74.3% of the patients with traditional surgery, 85.7% of the cases that used 3D printed models, and 100% of navigation-guided cases.[36] In a larger study, MIO resulted in a significant reduction in postoperative diplopia for complex fractures and reduced the rate of revision surgery from 20% to 4% in 113 orbital fracture repairs.[33]

Flexible Robotic Technology

Flexible robotic technology for endoscopic sinus and skull base surgery has been in development for the past decade[37] but is not yet in clinical use. Ideally, flexible robotic endoscopes would allow for endoscopes to curve around critical structures to reach surgical targets based on patient anatomy. A recent systematic review assessed 11 robotic prototypes for extended skull base surgery and concluded that although there are still technical limitations, clinical feasibility is getting very close.[38] A robotic endoscope holder for anterior skull base surgery was recently introduced, and 30 skull base surgeons were tested on 2 tasks with and without EndoscopeRobot, a robotic endoscope holder.[39] There was a trend toward shorter completion times and increased efficiency in one of the bimanual tasks.

Development of robots for the skull base and the head and neck is being developed on surgical robot platforms such as the RAVEN II including simulation of semiautonomous brain tumor ablation.[40] This research platform robot is important to study because any robot that is cleared by Food and Drug Administration has limitations on its use and cannot be modified.[41] In the research phase, multiple studies have demonstrated both feasibility and have reported the technical limitations. For example, access to the anterior cranial fossa was evaluated on both DaVinci and RAVEN robotic platforms in multiple studies (**Fig. 4**).[42–45] The conclusions were that instrument arms often collided due to the narrow funnel effect of surgical portals too close in proximity. Expanding the surgical portals did improve that, but surgeons were still limited by the ability to instrument at the target location.

BARRIERS TO ADOPTION AND STRATEGIES

Barriers to Robotics in Pediatric Otolaryngology

Barriers to pediatric robotic surgery are similar to those for adult TORS with a few additional limitations. Similar to adult TORS, cost becomes less prohibitive if cases are gathered at a tertiary center.[3] Cumbersome setup and decreased tactile feedback when compared with endoscopic instruments are barriers to adoption.[7] It can be prohibitive in a busy pediatric center with a large variety of cases. As robotic instruments continue to improve, the size of the instruments has become less of a limitation, as one study noted use of TORS in a 14-day-old. However, the same study noted the need for pediatric airway instruments, as many TORS instruments are designed for pharyngeal surgery.[5] Thus far, studies have only been able to show the noninferiority of robotic

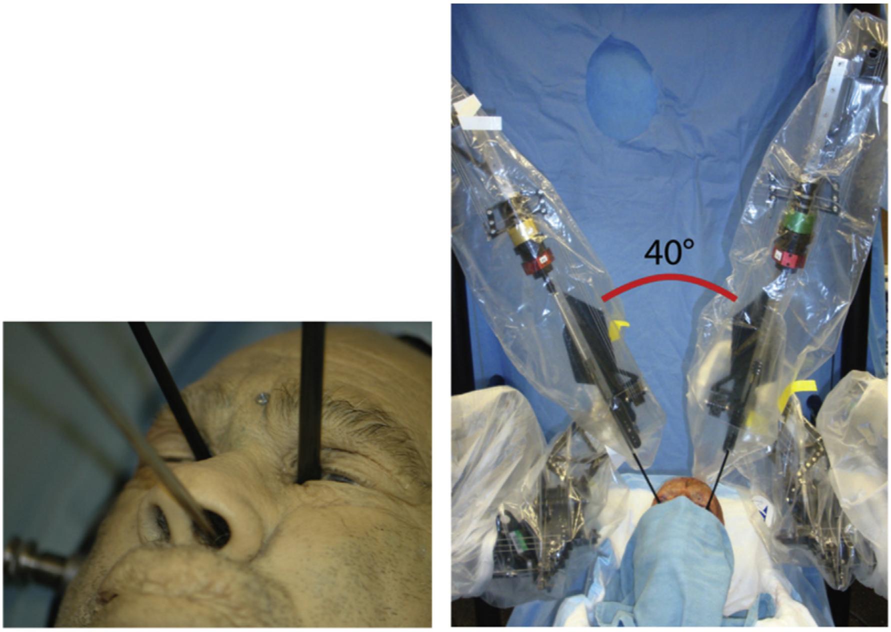

Fig. 4. Multiportal technique with the Raven robot in a cadaver study. (*From* Bly RA, Su D, Lendvay TS, et al. Multiportal robotic access to the anterior cranial fossa: a surgical and engineering feasibility study. Otolaryngol Head Neck Surg 2013;149(6):940-6 https://doi.org/10.1177/0194599813509587[published Online First: Epub Date]|.)

pediatric surgery. Improvement of the aforementioned limitations may result in the adoption of robotic surgery over endoscopic tools.

Barriers to Preoperative Planning with Virtual Reality

Surgical planning with virtual reality and other visualization methods has been demonstrated to provide insight that can change surgical approach and potentially improve patient outcomes. However, the time of experts needed to create an accurate model continues to be a barrier for widespread adoption as high fidelity simulations require increased time for image rendering as well as manual segmentation.[13] Lower fidelity environments allow for comparison to cadaver surgery and training but do not always provide experts with the soft tissue specifications needed to plan surgery.[18] Virtual reality used for planning of sleep surgery would also incur costs of scanning time and radiation exposure the patient may not otherwise need.[15]

Barriers to Preoperative Planning with Three-Dimensional Printing

3D printing combined with 3D models to plan and print cutting guides and markers are being quickly adopted due to their high clinical utility and increase in surgical efficiency.[20,22,23,28] Cost of printing the model is not usually prohibitive due to significant advances in 3D printing technology. However, commercial programs and expertise are needed to print 3D models with cutting guides, which incurs additional cost. Furthermore, expert surgeons currently determine appropriate cuts, and the margin of resection may change compared with what is predicted on the preoperative imaging. Adding an additional step of modeling may seem unnecessary without more studies showing superiority in patient outcomes compared with the current standard.

SUMMARY

Robotic surgery has been successfully applied to many different areas of pediatric head and neck surgery from sleep surgery to airway reconstruction to resection of pharyngeal masses. Despite some limitations including cumbersome setup and obtaining surgical access for robotic arms, overall studies have shown the feasibility and advantages of the surgical robot in pediatric otolaryngology. However, adoption has been limited, and robotic surgery may be better integrated into practice with advanced preoperative surgical planning, which allows for comparison of different surgical approaches. Computer-aided surgical planning techniques include current technologies of 3D printing and virtual reality as well as new developments of multiobjective cost function for optimization of approach, MIO, and flexible robotics. These promising robotic and advanced surgical planning technologies are more likely to be adopted with future studies noting advantages over current practice. More studies need to be done with actual patient outcomes as well as comparing the different methods.

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DISCLOSURE

Dr N. Konuthula has nothing to disclose. Dr R.A. Bly is co-founder and holds a financial interest of ownership equity with Edus Health, Inc and EigenHealth, Inc. He is Consultant and stock holder, Spiway, LLC.

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