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Michael E. Kupferman
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Atlas of Head and Neck Robotic Surgery

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Ziv Gil
Israel Institute of Technology
The Head and Neck Center
Rambam Healthcare Campus
Haifa, Israel

Moran Amit
Israel Institute of Technology
The Head and Neck Center
Rambam Healthcare Campus
Haifa, Israel

Department of Head and Neck Surgery
Houston, TX, USA

Michael E. Kupferman
Department of Head and Neck Surgery
MD Anderson Cancer Center
Houston, TX, USA

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To my children Ada, Izhar, Yanai and Elisheva that their spirit is carried within me.

Ziv Gil

For my parents, who tried, and my wife, Heli.

Moran Amit

For my wife, Debra, and our children Asaph, Gabrielle and Jacob.

Michael E. Kupferman

Biography

Professor Gil is a Barbara S. Goodman Endowed Investigator (ICRF) and the chairman of the Department of Otolaryngology—Head and Neck Surgery, Rambam Healthcare Campus, Israel Institute of Technology. He holds an MD/PhD degree in biophysics and neuroscience and is also the head of the Applied Cancer Research Laboratory and a member of the Rappaport Research Institute and the Clinical Research Institute at Rambam. He received his training at Memorial Sloan Kettering Cancer Center and the University of Pittsburgh Medical Center. He received awards from the Israeli Parliament, NY Head and Neck Society, Israeli Cancer Society, and Folks Foundation and multiple international research grants. He is the author of three books and 200 scientific publications and book chapters. Dr. Gil established new techniques in skull base and robotic surgery. He serves on the editorial boards of multiple journals including *Otolaryngology—Head and Neck Surgery*, *Journal of Neurological Surgery, Head and Neck*, and more. In 2014 he established the first comprehensive Head and Neck Center in Israel.

Moran Amit, MD/PhD, in cancer biology and immunology, completed his training in head and neck surgery at the University of Texas MD Anderson Cancer Center, Houston, Texas, USA. Dr. Amit's clinical focus is on robotic head and neck surgery (especially trans-oral robotic approaches to the oropharynx and parapharyngeal space, TORS) and functional rehabilitation of head and neck cancer patients. Dr. Amit is a co-founder of the Adenoid Cystic Carcinoma International Study (AXIS) Group and a board member of the International Consortium for Outcome Research (ICOR) in Head and Neck Cancer. He is a board member of the The European academy of tumor immunology and a member of the American Association for cancer research and the International Papillomavirus Society. Dr. Amit has published extensively in the areas of oral cavity, skull base, and salivary gland cancer. He received awards from the Chief Officer, Medical Corps, Israel Defense Forces, American Head and Neck Society, Israeli Cancer Society, and multiple international research grants for his research on tumor immunology and resistance to treatment. Dr. Amit is a Barbara S. Goodman Endowed Investigator (ICRF).

Dr. Michael Kupferman is an Associate Professor of Head and Neck Surgery at the University of Texas MD Anderson Cancer Center. He is an internationally-recognized expert in Head and Neck Oncology, with expertise in the surgical management of pediatric head and neck cancer and skull base tumors. His clinical practice focuses on upper aerodigestive tract cancers, melanoma, salivary gland and skull base tumors, as well as robotic surgery of the head and neck. Dr. Kupferman is also the medical director of the Voice Center at MD Anderson, and is the leader for clinical trials exploring the role of transoral robotic surgery for head and neck cancer. Dr. Kupferman is also a physician executive in the MD Anderson Cancer Network, where he leads the development, management and growth of clinical oncology programs across the Cancer Network. He obtained his medical degree from the University of Pennsylvania School of Medicine and completed residency in Otolaryngology—Head and Neck Surgery at the Hospital of the University of Pennsylvania. He also completed a combined clinical and research fellowship in advanced Head and Neck Surgical Oncology at MD Anderson Cancer Center. He has published over 125 peer-reviewed manuscripts and book chapters, and his laboratory research in the mechanisms of metastasis has been funded by the National Institutes of Health, American College of Surgeons, American Head and Neck Society, AAO and numerous private foundations.

Contents

Robotics in Surgery

1

Moran Amit, Shorook Na’ara, and Ziv Gil

1.1 Introduction

Over the last two decades, robotic-assisted surgery has revolutionized minimally invasive surgery in multiple surgical specialties. The first robotic surgery system, the PUMA 560, was developed in 1985 to provide greater precision in performing image-guided intracranial biopsies. Further refinement in the early 1990s led to ROBODOC, which was the first robotic system to receive FDA approval for arthroscopic hip surgery in 1994 [1]. Interest in medical robots led to collaborative efforts between the National Aeronautics and Space Administration (NASA) and Stanford Research Institute (SRI) in the early 1980s, to develop telepresence surgery, the virtual placement of a remotely located surgeon in the operative field.

Experience with minimally invasive laparoscopic procedures has helped surgeons understand the limitations of rigid equipment and two-dimensional views. This has resulted in the development of semirigid robotic equipment with three-dimensional views for the operative setting. Combining these tools with telepresence surgery led to the development of the Automated Endoscopic System for Optimal Positioning (AESOP), a robotic arm (controlled by a surgeon’s voice commands) that manipulates an endoscopic camera [2]. The first robotic system that enabled surgery over a large distance consisted of two separate subsystems, i.e., “surgeon-side” and “patient-side” (ZEUS, Computer Motion, California). The operator site was located in New York and the animals were in Strasbourg. The two sites were connected through a high-speed terrestrial optical-fiber network that transports data through dedicated connections using asynchronous transfer mode (ATM) technology [3].

Shortly thereafter, Intuitive Systems (Sunnyvale, CA) released the SRI Telepresence Surgery System that was recently updated to the current da Vinci Surgical System, the most common robotic system in use today [4].

In short, the current da Vinci system functions as a master-slave robot, with the surgeon manipulating instruments connected by a cable network to the robotic cart. The system comprises three arms (one for the 12 mm 0° or 30° camera and two accommodate 8 mm and 5 mm instruments). The camera not only enables magnification but also three-dimensional viewing of the surgical field.

M. Amit, MD, PhD • S. Na’ara, MD
Z. Gil, MD, PhD (✉)
The Head and Neck Center, Department
of Otolaryngology Head and Neck Surgery,
The Laboratory for Applied Cancer Research,
Rambam Healthcare Campus, Clinical Research
Institute at Rambam, Rappaport Institute of Medicine
and Research, The Technion, Israel Institute
of Technology, Haifa 66036, Israel
e-mail: ziv@baseofskull.org;
g_ziv@rambam.health.gov.il

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Robot-assisted surgery enables excellent visualization and the capacity to manipulate and resect tumors due to the six degrees of freedom offered by the robotic arms and by the camera.

1.2 Applications in Fields Other Than Otolaryngology

Robot-assisted surgery is currently utilized in almost every surgical field. In general surgery, there is an abundance of reports on its use in cholecystectomy, Heller myotomy, Nissen fundoplication, bowel resection with reanastomosis, splenectomy, and Whipple and hepatobiliary surgery [5]. These reports endorse the benefits of stable visualization and improved dexterity of the robotic arms with suturing and dissection. Cardiothoracic surgeons used robotic surgery first in 1998 to perform coronary revascularization procedures and mitral valve replacements [6]. Numerous additional case series have since been published, describing esophagectomy, lung resection, tumor resections, atrial fibrillation ablations, and congenital cardiac anomalies. Results have been encouraging, with evidence demonstrating fewer blood transfusions, shorter hospital stays, faster returns to preoperative function levels, and improved quality of life compared to patient series of sternotomy [7]. Multiple pediatric surgery robotic-assisted procedures include tracheoesophageal fistula repair, cholecystectomy, Nissen fundoplication, Morgagni's hernia repair, Kasai portoenterostomy, and congenital diaphragmatic hernia repair.

Gynecologists utilize robotic surgery in hysterectomies, myomectomies, and tubal reanastomoses and achieve similarly positive results as in laparoscopic and open procedures. However, a recent Cochrane review showed an uncertain benefit for robotic surgery in gynecology because it is unclear if it affects rates of complications [8]. Oncologic outcomes were similar to laparoscopic and open methods. The setup time for both exposure and docking of the robotic arms is longer with robot-assisted surgery but may be associated with a shorter hospital stay following hysterectomy. In addition, gynecologic surgeons observed another major disadvantage; the lack of haptic feedback, which is a virtual tactile feedback technology that provides mechanical feedback to the surgeon. Currently, in the United States, robotic-assisted hysterectomy is mainly used for benign conditions and has been shown to be more expensive than conventional laparoscopic hysterectomy, with no difference in overall rates of complications [9].

The development of robotic technology has paved the way for the performance of highly complex procedures such as transplant surgery, in a minimally invasive fashion. The first fully robotic kidney transplantations were performed in the late 2000s. The use of the robotic-assisted approach has enabled transplantation of kidneys with minimal complications and has significantly shortened the recovery period. This has made possible kidney transplantation in obese patients, who were frequently denied access to transplantation.

The field of urologic surgery has perhaps seen the greatest incorporation of robotic surgery: To date, more than two-thirds of prostatectomies are performed with robotic assistance [10]. Positive margin status and PSA levels achieved by the robotic technique are comparable to those achieved by open procedures [11]. However, surgeons noted significantly lower blood loss and transfusion rates, less pain, and shorter hospital stays for robotic techniques than open prostatectomies; erectile and urinary functional outcomes were found to be equivalent among open, laparoscopic, and robotic prostatectomies [12].

1.3 Evolution of Robotic Applications in Otolaryngology

The first TORS procedure was reported in Washington by McLeod et al. only a little more than one decade ago [13]. Since then, surgeons have laid infrastructure for its use, and it has been successfully incorporated into routine practice in the field of otolaryngology. Incorporation of robotic-assisted surgery in otolaryngology can be attributed to three main driving forces: (1) technological advancements that improved visualization and instrumentation, (2) fast learning curve, and (3) better understanding of head and neck cancer biology while exploring organ conservation treatment protocols.

Traditionally, surgical removal of oropharyngeal cancer required mandibulotomy with or without free flap reconstruction in most cases. Unfortunately, this approach results in significant morbidity. Mandibulotomy patients often require tracheotomies and feeding tubes. In addition, postoperative recovery, including rehabilitation, might further be slowed by adjuvant chemotherapy and/or radiation [14]. The pendulum started to shift in the late 1980s when multiple institutions investigated alternative treatment protocols based on organ preservation. The VA trial and RTOG 91-11 showed that survival rates following chemotherapy and radiation protocols were equivalent to those for patients who underwent surgery followed by radiation. By preserving the functional laryngopharyngeal complex, these protocols became the standard of care in the treatment of squamous cell carcinoma of the larynx [15, 16]. Alongside the highly conformal radiation delivery techniques (e.g., IMRT), molecular targeted therapies (e.g., cetuximab) were successfully introduced and represent an evolutionary advancement in head and neck cancer management. Nonetheless, survival and quality of life are still poor for some patients [17].

Over the last decade, we encountered an increase in oropharyngeal squamous cell carcinoma (OPSCC) caused by the human papilloma virus (HPV). HPV was recognized as a powerful prognostic biomarker for responsiveness to radiotherapy; however, HPV-positive patients tend to be younger, and thus the potential is greater for long-term sequelae from radiation, such as radiation-induced malignancy [18]. The development of successful minimally invasive surgical techniques has assisted in achieving sound oncological resection with local control and possibly sparing patients from undergoing concurrent chemoradiation.

First attempts to control OPSCC with minimally invasive techniques in the modern radiotherapy era used transoral laser microsurgery (TLM). While no randomized trials have compared surgery and radiation, small series from various institutions have shown success at achieving local control by using TLM as the primary modality for OPSCC [19]. However, rigid narrow field exposure through laryngoscopes is very limited and challenging to maneuver within the complex anatomy of the oropharynx.

Robotic surgery overcomes some of these limitations and provides a unique advantage by introducing angled optics and instrumentation with multiple degrees of rotation, which allows access to the entire upper aerodigestive tract surface. In addition, superior optics enable a precise three-dimensional assessment of resection margins, less collateral tissue damage, and an excellent view of the surgical bed.

1.4 Feasibility

Robotic-assisted salivary gland excision and neck dissection in a porcine model were the first applications of robotics in otolaryngology, as documented at Stanford University in 2003 [20]. Among the advantages claimed were the elimination of hand tremor and superior visualization without tactile sensation. Next, Hockstein and O’Malley reported gaining wide access to the laryngopharynx using mouth gag retractors in an airway mannequin and cadaver [21]. Later, Weinstein performed a supraglottic laryngectomy in a canine model [21]. The authors reported increased exposure with the mouth gag, yielding adjustable visualization of the larynx [22]. The final step before attempts on live human surgery was the technological increment achieved by coupling of 5-mm instruments and other mouth retractors to the robotic system at Cleveland Clinic by Solares [23]. The latter incorporated the CO2 laser with the robotic arm for robotic-assisted supraglottic laryngectomy and demonstrated the importance of evaluating variable patient factors such as oral opening and neck extension.

Weinstein and O'Malley first reported the efficacy of robotic-assisted head and neck surgery. They described a series of patients with early-stage, base of tongue squamous cell carcinomas who underwent complete en bloc resection of their tumors with negative margins. No immediate complications were noted, and patients were able to return to a full diet within 6 weeks of surgery [24]. With the feasibility of TORS established in OPSCC, institutions have begun recruiting patients for clinical trials such as ECOG3311 and RTOG1221 to assess treatment de-escalation of HPV+ patients with surgery and surgical intensification of treatment in HPV patients. Currently, robotic-assisted surgery has a wide range of applications in otorhinolaryngology. These include transoral surgery for sleep disorders, malignant and benign tumor resection from the upper aerodigestive tract, and skull base surgery. In addition, various approaches have been utilized for neck surgery, i.e., the transaxillary approach for thyroid and parathyroid surgery, and the retroauricular approach for neck dissection, congenital lesion resection, and salivary gland surgery. Table 1.1 summarizes published applications of robotic-assisted surgery in otorhinolaryngology.

Table 1.1. Published applications of robotic-assisted surgery in otorhinolaryngology

Approach	Site	Pathology	Number of published cases	References
TORS	Oral cavity	Malignancies	8	[25–27]
	Oropharynx: base of tongue and tonsils	Malignancies	1,337	[24–36]
		Benign lesions	19	[13, 37–39]
		OSA	726	[40–50]
	Hypopharynx	Malignancies	21	[26, 27, 51–53]
	Larynx: supraglottis and glottis	Malignancies	63	[23, 25–27, 34, 51, 54–56]
		Congenital malformations and benign lesions	6	[57, 58]
	Parapharyngeal space	Benign and malignant tumors	45	[59–67]
Transaxillary approach	Thyroid	PTC and benign nodules	2,074	[68–79]
	Parathyroid	Parathyroid adenoma and hyperplasia	15	[78–81]
Thoracoscopic approach	Mediastinal parathyroid	Parathyroid adenoma and hyperplasia	10	[82–87]
Retroauricular/postauricular approach	Thyroid	PTC	4	[88]
	Neck dissection		19	[27, 89]
	Branchial cleft cyst		3	[90]
	Submandibular gland		13	[91]
	TGDC		1	[92]
Modified facelift	Neck dissection		44	[27, 93]

TORS transoral robotic surgery, *OSA* obstructive sleep apnea, *PTC* papillary thyroid carcinoma, *TGDC* thyroglossal duct cyst

1.5 Oncologic and Functional Outcomes

The effectiveness of a therapeutic modality appears to be strongly inversely related to the number of clinical trials that investigate the modality. While most head and neck cancers are surgically treated, only few clinical trials isolate any given surgical question.

Long-term survival outcomes of TORS are not currently available. Still, several institutions have published promising small cohort short-term data. A phase I study of 27 patients with early-stage tonsillar squamous cell carcinoma undergoing TORS revealed a 92 % negative margin rate. Population-based analysis revealed that TORS is associated with a lower rate of positive margins than non-robotic surgery and that high-volume centers have the lowest rates of positive margins and unplanned readmissions [28]. After achieving resection with negative margins, adjuvant treatment may be administered. However, even if the patient requires adjuvant therapy, the toxicity from the lower dose of radiation, with possible sparing of concurrent chemoradiation, tends to be significantly less following adequate robotic surgery and to result in better functional outcomes [94]. In addition, most patients do not need a tracheotomy or extended hospitalization.

From a functional standpoint, many clinical studies have shown improved post-TORS swallowing function compared with other surgical modalities and compared with primary chemoradiation therapy, along with shorter hospital stay and faster recovery, as well as a more efficient return to work after completion of therapy [29]. Most patients after TORS for OPSCC maintain full oral feeding and eventually acceptable to normal physiological swallowing. In a negligible minority of patients, elective temporary tracheotomy (1–2 weeks) is performed at the discretion of the surgeon, based on the estimated risk of postoperative upper airway obstruction due to mucosal swelling and the risk of postoperative bleeding. Faster recovery means that adjuvant therapy, if indicated, may start sooner, which improves locoregional control [30, 31].

Favorable oncological and functional outcomes of TORS, which permit resection of the tumor en bloc while preserving patients' swallowing ability, led the FDA to approve, in December 2009, TORS for use in selected benign and malignant tumors of the head and neck. Using TORS, a mandibulotomy and/or pharyngotomy is avoided. As evidence accumulates regarding survival implications of HPV status in patients undergoing primary surgical therapy, TORS may play a significant role in the application of surgery to escalate or de-escalate first-line treatment for select patients with OPSCC.

1.6 Cost

High costs are a significant concern and a potential disadvantage of the implementation of a robotic program solely for TORS. With an initial cost of 1.5 million US dollars and annual maintenance fees of 100,000 US dollars, most programs rely on sharing the robotic facility with other departments. Disposable equipment such as graspers, cautery arms, and other surgical instruments total approximately 200 dollars per case. A nationwide cross-sectional analysis of more than 9,000 patients showed that after controlling for all other variables, TORS patients had lower rates of gastrostomy tube placement and tracheotomy tube placement, shorter length of hospitalization (mean, −1.5 days), and lower hospital-related costs (mean, −$4,285) [95].

1.7 Training

Naturally, as the popularity of robotic surgery is growing, practitioners are seeking training and certification in this area. The pitfall of such market-driven health care is the possibility that adverse outcomes may decrease positive results of surgery when less-experienced surgeons perform oncologic resections simply because TORS is a new and marketable procedure [96]. Intuitive surgical provides a training curriculum on their website, which includes didactic lectures on the da Vinci console, cadaver dissections, and live case observation. Nearly 1,500 surgical clips of TORS can be viewed on YouTube, and representatives for the company provide surgeon tutoring during practitioners' initial procedures.

Robust outcomes data are not yet available, but potentially, robot-assisted surgery will become a standardized integral part of treatment protocols such as the National Comprehensive Cancer Network (NCCN). Once integrated, the implementation of a standardized curriculum for robotic surgery into residency and fellowship education will be vital. Current data indicate that the performance of simple tasks such as grasping inanimate objects and suturing on latex is highly intuitive, and introducing residents to basic robotic surgical skills eases their transition to live patient cases [97]. As a result, many training programs now provide cadaver dissection courses using the robot as part of their training. Training is discussed in more depth in Chapter 4.

1.8 Future Directions

To date, available data on head and neck robotic surgery, mainly TORS, indicate that it is a safe efficacious procedure for benign conditions such as obstructive sleep apnea. As stated, current efforts are being directed to implement TORS in oncology treatment protocols. Attempts are also being made to extend the applications of robot-assisted surgery and to use TORS in innovative ways and in other areas in the head and neck. An example is the field of skull base surgery, which requires precise motions with a steady hand. Surgeons have illustrated an approach to the midline and anterior skull base using two trocars inserted transcervically and placing the camera head in the oral cavity [98]. Anterior skull base and sella were accessed and dissected via bilateral Caldwell Luc incisions and maxillary antrostomies [99].

Robotic-assisted surgery is also being utilized in reconstructive surgery [100]. Microvascular anastomosis in narrow and deep spaces such as the oropharynx has been shown to be fast and effective, in a tremor-free manner. TORS free flap oropharyngeal reconstruction provides improved functional recovery and avoids the need for long-term healing by secondary intention of the oropharyngeal defect.

As current instrumentation is bulky, rigid, and passive, access is limited to narrow 3D complex spaces such as the larynx and skull base. Approaches to such areas will become possible as finer analytical instrumentation such as flexible lasers and Doppler probes will emerge. To overcome some of these obstacles, a flexible nonlinear robot was designed based on the experience gained by the use of the da Vinci system. This robot was further customized and transformed into the Medrobotics(®) Flex(®) System (Medrobotics Corp., Raynham, MA, USA), which was developed specifically for use in surgical applications requiring nonlinear maneuverability such as transoral surgery. The Medrobotics® Flex(®) System is an operator-controlled flexible endoscope system that includes rigid chip-on-tip endoscope and computer-assisted controllers, with two external channels for use with compatible, 3.5 mm flexible instruments. In 2015, the FDA approved the use of the Flex System for transoral resections of head and neck tumors.

Conclusion

Head and neck applications of robotic surgery are an evolutionary increment in surgical capabilities. While robotic-assisted head and neck surgery confers significant advantages, its limitations should be acknowledged. Patients can benefit from en bloc removal of their tumors via minimally invasive surgery without a cervical incision while preserving function and potentially avoiding adjuvant radiation and long-term sequelae. While long-term oncologic and functional data are needed to fully validate its use, early results are promising.