Robotics in otorhinolaryngology – head and neck surgery

A look at the past, present and future

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Following the introduction of robotics in otorhinolaryngology – head and neck surgery in 2005, trans-oral robotic surgery (TORS) has led to a paradigm shift in the treatment of upper aerodigestive tract neoplasms. By offering the possibility of sparing the patient from the toxicity of chemoradiotherapy – either as a single modality therapy or, where adjuvant therapy is required, through dose de-escalation – TORS provides a unique opportunity for pushing the boundaries in the treatment of head and neck cancer beyond 'organ preservation' to 'function preservation'. Another key role for TORS is in the evaluation and treatment of carcinoma of unknown primary (CUP). Through the supreme visualisation and manoeuvrability offered, tongue base mucosectomy has been shown to enhance the diagnostic yield in those challenging cases and is now incorporated in the most recent NICE guidelines for the evaluation of CUP. By removing the diagnostic uncertainty in terms of primary tumour origin, TORS allows for a more targeted approach thus reducing treatment-related morbidity. However,

the role of TORS does not stop in the treatment of cancer. TORS has been shown to be a highly effective multi-level treatment for obstructive sleep apnoea in patients failing to tolerate conventional treatment(s). Moreover, robotic surgery enables the performance of thyroidectomy and parathyroidectomy by completely avoiding a neck scar, which is a key concern for patients prone to hypertrophic and keloid scarring. Finally, novel flexible and miniaturised autonomous robots are being developed to assist in procedures requiring high surgical precision, such as in the fields of otology and endoscopic skull base surgery.

Introduction

Following the successful completion of pre-clinical studies in 2005,¹ robotic surgery was introduced in the clinical setting in otorhinolaryngology – head and neck surgery (ORL–HNS) by Professors Bert O'Malley and Gregory Weinstein at the University of Pennsylvania in 2006.² Using the da Vinci® surgical robot (Intuitive Surgical®, Inc., Sunnyvale, CA), they demonstrated the safety and feasibility of trans-oral robotic resection for tongue base

Figure 1 Timeline illustrating the milestones characterising the first decade (2005–2015) of robotic surgery in otorhinolaryngology – head and neck surgery.

neoplasms, coining the term ‘TORS’ (as an acronym for Trans-Oral Robotic Surgery).² Indications for TORS quickly expanded to include a number of benign and malignant diseases involving various anatomical subsites in the head and neck. Beyond oropharyngeal cancer, TORS was subsequently shown to be a valuable treatment for obstructive sleep apnoea, as first described by Professor Claudio Vicini at the University of Pavia in 2010.³

Another important area relates to scarless-in-the-neck thyroid and parathyroid surgery. Prior to robotics, the limitations associated with conventional endoscopic surgery had stalled the technique. The first transaxillary robotic thyroidectomy was performed by Professor Woong Youn Chung at Yonsei University in 2009.⁴ Following modifications to Chung’s technique, Professor Neil Tolley performed the first robotic parathyroidectomy at St Mary’s Hospital, Imperial College London in 2011.⁵ The role of transaxillary robotic surgery evolved to include a variety of head and neck proce-

dures, including neck dissection. New routes for robotic thyroidectomy were also described, including the facelift approach first described by Professor David Terris at Augusta University in 2011.⁶ The milestones characterising the first decade (2005–2015) of robotic surgery in ORL–HNS are pictorially presented in a timeline in Fig 1.

This article discusses the main procedures undertaken robotically in

ORL–HNS and provides an assessment of their impact in the field. The future role of robotics in ORL–HNS is also explored.

Trans-oral robotic surgery

TORS capitalised on the presence of the oral cavity as an access point for Natural Orifice Transluminal Endoscopic Surgery (NOTES), thus providing access to the pharynx, parapharyngeal space and larynx without

Table 1 TORS application in head and neck surgery. TORS, Trans Oral Robotic Surgery; CPAP, Continuous Positive Airway Pressure *Asterisk denotes TORS procedures at a pre-clinical (cadaveric) phase

TORS procedures in otorhinolaryngology – head and neck surgery
Oropharyngeal resection (including for advanced oropharyngeal carcinoma) ⁹
Resection of parapharyngeal space tumours ¹⁰
Supraglottic laryngectomy ¹¹
Trans-oral robotic total laryngectomy ¹²
Hypopharyngeal resection ¹³
Evaluation and treatment of carcinoma of unknown primary ¹⁴
Obstructive sleep apnoea surgery (in patients not tolerating CPAP) ^{15–17}
Resection of paediatric head and neck masses ¹⁸
Free flap reconstruction of large oropharyngeal defects ^{19,20}
Nasopharyngectomy ^{21*}
Hypophysectomy and anterior skull base surgery ^{22*}

Figure 2 Patient one year after primary chemoradiotherapy for head and neck cancer. Note extensive telangiectasiae and pronounced varicosities over the neck and chest. This patient suffered a cerebrovascular accident due to accelerated carotid atherosclerosis as a result of treatment.

Figure 3 Operating room setup for TORS. Central robotic arm holds 12mm 30° up stereoscopic endoscope (this can be alternated with a 0° stereoscopic endoscope depending on site of surgery). Right 5mm robotic arm holds the monopolar electrocautery (15J, blended mode) – this can be alternated with a 273-µm thulium laser fibre. Left 5mm robotic arm holds a long tip Maryland dissection forceps.

the morbidity of cervical incisions and associated disruption of the pharyngeal musculature or the limitations associated with previously described trans-oral approaches, namely trans-oral laser microsurgery (TLM).⁷

Within a decade, TORS evolved from proof-of-concept to standard-of-care in high-volume robotic centres after

it obtained FDA approval both for benign and malignant diseases in 2009.⁸ The different TORS applications in ORL–HNS are illustrated in Table 1, with the most established discussed individually in their respective sections.

TORS for oropharyngeal carcinoma

Oropharyngeal carcinoma represents the most established application for TORS. There are several reasons for this. First, the epidemiology of oropharyngeal squamous cell carcinoma (SCC) has changed, with its incidence rising in the past three decades despite a decline in both smoking rates and the overall incidence of head and neck SCC.²³ Second, this increasing incidence tends to preferentially affect younger patients who (unlike ‘traditional’ SCC patients) are not generally smokers and heavy drinkers. This has been attributed to human papilloma virus (HPV) infection.²⁴ HPV-positive oropharyngeal carcinoma is associated with a far better prognosis than its HPV-negative counterpart, and this difference in tumour biology is also reflected in the eighth edition of the American Joint Committee on Cancer (AJCC) tumour, node, metastasis (TNM) staging system, which now accounts for HPV status.²⁵ Third, the long-term toxicity of chemoradiotherapy is widely recognised, including the development of metachronous radiation-induced sarcomas and the deleterious systemic effects of cytotoxic drugs (Fig 2).²⁶ Those severe long-term sequelae of primary chemoradiotherapy become especially relevant in those younger HPV-positive patients who naturally have a longer life expectancy.

The above concerns relating to chemoradiotherapy brought surgery back into the spotlight as a primary treatment option for oropharyngeal carcinoma. Through its unique features – including a 3D magnified view, wristed robotic instruments operating with seven degrees of freedom, and enhanced surgical dexterity as a result of tremor-filtering and motion-scaling – TORS offers unprecedented visualisation, access and ergonomics (Fig 3).²⁷ By overcoming ‘line-of-sight’ issues associated with TLM, which only permits tangential cutting, TORS allows the en-bloc resection of the tumour with surrounding tissue margins (Fig 4).²⁸ This is especially important because the main criticism around TLM relates to the frequent need for piecemeal tumour resection, which is thought to violate the principles of surgical oncology.²⁹ In this way, TORS greatly increases the scope of tumours that can be resected trans-orally far beyond its predecessor (TLM), without having to compromise on how the oncologic resection is performed.²⁸

It is important to appreciate that the evidence for TORS primarily relates to its role as a treatment of early-stage oropharyngeal cancer (stages I and II) and that – even for this – it remains limited to level II, with a recent Cochrane review failing to identify any randomised controlled trials (RCTs).³⁰ This, however, is not unique to TORS but instead represents a well-recognised limitation in surgical research.³¹ Despite this, the existing evidence is promising. A recent systematic review of 20 case series involving more than 2,000 patients showed that the oncological outcomes (including overall survival and locoregional control) are

Figure 4 TORS right lateral oropharyngectomy. Note superior constrictor muscle exposure following en-bloc resection of T2 oropharyngeal carcinoma with negative margins in all 3 dimensions on intraoperative frozen sections. This patient was spared the need for adjuvant treatment.

Figure 5 TORS supraglottic laryngectomy for T1 tumour of laryngeal surface of epiglottis.

equivalent between TORS and intensity modulated radiotherapy (IMRT) for early oropharyngeal carcinoma – with TORS achieving superior functional outcomes, including for swallowing and quality of life (QoL).³² Moreover, there is now emerging evidence from high-volume centres for the role of TORS in advanced oropharyngeal cancer (stages III and IV),⁹ as well as for residual and recurrent disease.³³

TORS offers the possibility of sparing the patient from the toxicity of chemoradiotherapy – either as a single modality therapy or, where adjuvant therapy is required, through

dose de-escalation. Three multicentre RCTs, which aim to answer important questions around the role of TORS in the treatment of oropharyngeal carcinoma, are currently in the recruitment stage. These include the PATHOS trial for HPV-positive oropharyngeal cancer (UK),³⁴ the RTOG 1221 trial for HPV-negative oropharyngeal cancer (US),³⁵ and the ORATOR study for early-stage oropharyngeal cancer (Canada).³⁶

TORS partial and total laryngectomy

TORS supraglottic laryngectomy is now a fairly standard procedure in high-volume robotic centres (Fig 5).³⁷ It is the wide experience with TLM in performing trans-oral partial laryngeal surgery, combined with the shorter learning curve and improved ergonomics associated with TORS, which has facilitated its adoption as a treatment for laryngeal cancer.^{28,38} However, as with oropharyngeal cancer, patient selection is paramount because not all patients are candidates for TORS.³⁹

Preliminary results for TORS supraglottic laryngectomy are encouraging, not only in terms of the oncological outcomes achieved but also in terms of their functional outcomes.^{11,40} Thus, TORS provides a unique opportunity for pushing the boundaries in the treatment of head and neck cancer beyond ‘organ preservation’ to ‘function preservation’. It is becoming increasingly apparent that ‘organ preservation’ – a common argument in support of primary non-surgical treatment as the ‘gold standard’ first-line therapy for head and neck cancer – is meaningless unless ‘function preservation’ is also present

after treatment.⁴¹ The high long-term gastrostomy and tracheostomy dependence rates seen after chemoradiotherapy are a testament to this loss of function and call into question such ‘organ preservation’ advantages.^{41,42} Dysphagia and recurrent aspiration from radiation-induced fibrosis are not only common and debilitating complications of chemoradiotherapy but can also directly impact on overall survival.⁴³

Beyond TORS supraglottic laryngectomy, TORS total laryngectomy is also feasible and safe.⁴⁴ As this operation can only be performed robotically, TORS total laryngectomy represents a newly enabled surgical procedure. The limited dissection with this novel approach may prove valuable in reducing complications related to wound-healing, such as pharyngocutaneous fistula formation and anastomotic breakdown.^{12,45} These are both common and serious complications seen after salvage total laryngectomy, leading to an increased morbidity, need for revision surgery often with flap insertion, and even mortality.⁴⁶ Another possible indication for TORS total laryngectomy relates to non-functional larynx or chondronecrosis following radiotherapy in order to stop recurrent aspiration and pneumonia.⁴⁷

Evaluation and treatment of carcinoma of unknown primary with TORS

Another newly enabled surgical procedure with TORS is tongue base mucosectomy for the evaluation and treatment of carcinoma of unknown primary (CUP).¹⁴ CUP accounts for 2%–4% of newly diagnosed head and neck cancers and is associated with important dilemmas that may

significantly compromise the patients' QoL.⁴⁸ When the primary tumour cannot be identified despite clinical examination, anatomical (CT and MRI) and metabolic imaging (FDG PET-CT), and panendoscopy (pharyngo-laryngo-oesophagoscopy) with biopsies of high-risk areas (nasopharynx, oropharynx and hypopharynx) then the common approach recommended by the head and neck multidisciplinary team (MDT) is wide field radiotherapy (with or without chemotherapy depending on cervical nodal status, patient performance status and wishes among other factors taken into consideration by the MDT). This often involves total mucosal irradiation (of the entire upper aerodigestive tract). As expected, the associated morbidity of wide field radiotherapy can be substantial – particularly in relation to xerostomia, trismus, dysphagia, dentition, and osteoradionecrosis.⁴⁹

Through the supreme visualisation and manoeuvrability offered, TORS has been shown in several studies to enhance the diagnostic yield in those challenging cases.^{50–52} By removing the diagnostic uncertainty about

Figure 6 Tongue base mucosectomy and bilateral tonsillectomy specimens. Specimen orientation for the histopathologist is crucial.

primary tumour origin in up to 78% of CUP patients, TORS allows for a more targeted approach thus reducing treatment-related morbidity.⁵³ The importance of this becomes evident when considering that the majority of CUP patients are young, previously healthy males with HPV-positive tumours.⁵⁴ Tongue base mucosectomy (Fig 6) is now incorporated into the most recent NICE guidelines for the evaluation of CUP when all other existing diagnostic modalities including FDG PET-CT fail to reveal the site of the primary tumour.⁵⁵

TORS for obstructive sleep apnoea

Beyond cancer of the upper aerodigestive tract, another area where TORS has proven to be an invaluable tool is in the treatment of obstructive sleep apnoea (OSA).¹⁶ OSA represents a major public health problem affecting 10% of the population.⁵⁶ Although continuous positive airway pressure (CPAP) has been shown to be a highly-effective treatment, adherence rates fall below 50% pointing to the need for alternative treatment options.^{17,57} This is paramount, especially in cases of moderate and severe OSA where morbidity and mortality are significant.⁵⁸

As OSA is typically a multi-level disease,¹⁷ TORS represents an ideal multi-level treatment as a result of its superior visualisation and ergonomics.¹⁵ There is now an increasing body of evidence to support its safety and efficacy as a treatment for moderate-to-severe OSA.¹⁶ This does not only apply to patients failing to tolerate CPAP but also in patients who have 'failed' conventional (non-robotic) sleep surgery.⁵⁹ This has been linked directly to the

Figure 7 Volumetric MRI analysis before (left) and after (right) TORS posterior glossectomy for OSA illustrating the significant reduction in tongue base volume. This patient was cured of severe OSA.

improved visualisation, access, and manoeuvrability offered by TORS that cannot be matched by any other trans-oral means.^{15,39} Besides the improvements seen in objective and subjective clinical parameters – namely the Apnoea-Hypopnoea Index (AHI) and Epworth Sleepiness Score (ESS) respective – volumetric MRI analysis illustrates the improvement in terms of the upper airway following TORS for OSA (Fig 7).⁶⁰

There are now several studies and meta-analyses to support the role of TORS as a valuable multi-level treatment in OSA following failure of conventional treatment(s).^{3,15,59,61} A best evidence topic review by Garas *et al* in 2017, which reviewed the most up-to-date evidence on the subject, showed that TORS has been consistently reported to be effective in more than 75% of non-obese OSA patients and more than 50% of non-morbidly obese OSA patients (BMI=30–35 kg/m²) – although they also pointed out the absence of RCTs to support these findings.¹⁶ Following this article, TORS has been included by The Royal College of Physicians (London, United Kingdom) in their most recent Clinical Update Sleep Consensus Statement (2018) as a valid treatment option for multi-level OSA in non-morbidly obese patients (BMI ≤35 kg/m²) failing to tolerate CPAP.⁶²

Robotic thyroid and parathyroid surgery

Thyroid nodules, including differentiated thyroid cancer (DTC), are most commonly encountered in young women.⁶³ Naturally, this select patient group is the one most concerned about cosmesis.⁶⁴ This is especially relevant in the Far East where a horizontal neck scar is perceived to denote death – and this is where ‘scarless-in-the-neck’ endoscopic thyroidectomy originates from.⁶⁵ A number of extracervical approaches have been described for endoscopic thyroidectomy throughout the years, but the limitations of conventional endoscopic surgery stalled their uptake.⁶⁶

The introduction of robotic surgical technology re-ignited the interest around ‘scarless-in-the-neck’ endoscopic thyroidectomy. Transaxillary robotic thyroidectomy was first performed in South Korea in 2009 and proved to be a popular approach among the local population.⁴ In less than a decade, thousands of robotic thyroidectomy cases have been performed.⁶⁷ However, the vast majority is confined to South Korea, with the uptake in the western world being significantly lower.⁶⁸

Various factors have been implicated in the limited uptake of robotic

thyroidectomy and parathyroidectomy in western practice, which currently account for less than 1% of the total thyroid and parathyroid surgical volume (Table 2).⁶⁹ The largest barrier to adoption of robotic thyroidectomy is its prohibitive cost.⁷⁰ Differences in remuneration are likely to also play a role. In the western world, remuneration is based on the extent of thyroid surgery (and not the approach), whereas in South Korea the approach used is key for billing purposes because robotic thyroidectomy is reimbursed at four times the rate of open thyroidectomy and twice that of endoscopic thyroidectomy.^{71,72}

Beyond the financial and cultural reasons discussed, anthropometric features (primarily relating to obesity and height) make the procedure more technically demanding in western patients.^{69,73} In addition, the average thyroid nodule resected in South Korea – where a national thyroid cancer screening programme has been implemented for years – is much smaller (often sub-centimetre) and thus easier to resect compared with those in western patients.⁶⁹ Finally, an important barrier to the diffusion of robotic thyroidectomy in the western world is medicolegal concerns. Transaxillary robotic thyroidectomy has been associated with brachial plexus

Figure 8 A patient two weeks after right transaxillary robotic thyroid lobectomy. The incision is ‘hidden’ in the axilla. Note keloid on chest from previous skin mole excision. This is a patient who had valid reasons for wanting to avoid a visible neck scar and seeking a transaxillary approach for her right thyroid lobectomy.

neurapraxia, which is a complication unique to this approach. This makes it difficult to justify in view of its primary advantage being cosmetic.^{74,75} Indeed, this resulted in a medical device class II recall by the US Food and Drug Administration (FDA) in 2011.⁷⁶

Despite all of the above barriers, robotic thyroidectomy is successfully practised in high-volume institutions in the UK, Europe and the US, with outcomes (including oncological outcomes for DTC) equivalent to conventional thyroidectomy and superior cosmesis at the expense of time and cost (Fig 8).^{69,78,79} More recently, different robotic approaches have been described (such as the facelift and trans-oral), but these are still in the early stages, with no long-term or comparative data available to date.^{80,81}

Following robotic thyroidectomy, robotic parathyroidectomy was the natural next step.^{31,69} The technique was first performed in 2011 in London, UK, and involved a ‘scarless-

Table 2 Barriers to the uptake of robotic thyroidectomy and parathyroidectomy in the West (compared to South Korea). The last one (nodule size) applies only to robotic thyroidectomy as giant parathyroid adenomas are exquisitely rare.⁷⁷

Barriers to the uptake of robotic thyroidectomy and parathyroidectomy in the West	
Cultural	Different perceptions around neck scar
Anthropometry	Larger mean body habitus (obesity and height)
Cost	High cost, same remuneration irrespective of approach, longer operative time
Complications	‘New’ complications: brachial plexus neurapraxia
Medicolegal	FDA recall in 2011
Nodule size	Larger thyroid lobes and nodules (no national thyroid cancer screening programme)

Figure 9 The ‘extended salute’ position for transaxillary robotic thyroidectomy and parathyroidectomy. This minimises traction to the brachial plexus and thus the risk of postoperative neurapraxia

in-the-neck’ approach without the need for CO₂ insufflation.⁵ Preliminary results were promising because they demonstrated it to be a safe and feasible targeted parathyroidectomy approach in carefully selected patients.⁵ Arm-positioning was modified (from that originally described for transaxillary robotic thyroidectomy) to the ‘extended salute’ position (where the back of the patient’s hand rests on their forehead), and this was shown to significantly reduce the risk of brachial plexus neurapraxia (Fig 9).^{5,82}

A subsequent prospective non-randomised study comparing robotic parathyroidectomy with minimally invasive open parathyroidectomy demonstrated that, as with robotic thyroidectomy, the robotic parathyroidectomy approach provides superior cosmesis and is equivalent in terms of cure rate for primary hyperparathyroidism. The technique now considered as the ‘fourth generation’ in the evolution of parathyroidectomy (Fig 10).⁸² However, its uptake remains limited for the same principal reasons as those for robotic thyroidectomy.

From the above, it becomes apparent that robotic thyroid and parathyroid surgery are both feasible and safe in appropriately selected patients.^{5,69,82} However, as both operations are complex and technically demanding, their practice should be confined to high-volume surgeons only. Until their currently prohibitive costs are substantially reduced, their role is likely to remain in a niche capacity.⁶⁴ Novel robotic approaches (such as

the facelift and trans-oral) have also been recently described but further research is needed to establish their role (if any) in modern thyroid and parathyroid surgery.

The future

At present, the major limitation with regards to robotic surgery is its prohibitive cost.^{68,83} This is, however, likely to change in the near future with patents due to expire soon and novel robotic systems being introduced to the market. The resulting market competition is paramount because it will not only drive down costs but also enhance innovation.^{68,84}

In ORL–HNS, the more recently introduced robot is the Flex® Robotic System (Medrobotics® Inc., Raynham, MA), which is the first surgical robot to be specifically designed for TORS.⁸⁵ It has already received approval for human use, both in the European (CE mark 2014) and US (FDA clearance 2015) markets.⁸⁶ The Flex® Robotic System consists of an operator-controlled computer-assisted flexible endoscope with articulated segments, which – once positioned inside the patient’s mouth – can be fixed into the desired position.

The flexibility of the Flex® Robotic System represents a major improvement in robotic surgical technology likely to expand the range of procedures that can be performed with TORS. A number of recent cadaveric studies have demonstrated its feasibility for operating on the nasopharynx, hypopharynx, and cervical oesophagus.^{87,88} Moreover, early clinical results are also now emerging, which show it to be an optimal tool for glottic surgery – this was not possible

Figure 10 The ‘four generations’ of parathyroid surgery

with the da Vinci® surgical robot owing to the bulk of its robotic arms.^{89,90} Importantly, the Flex® Robotic System is less costly than the da Vinci® surgical robot.^{91,92}

Furthermore, multinational corporations are now heavily investing in Research and Development (R&D) to design their own surgical robots.⁹³ These include the two largest medical device manufacturers in the world: Medtronic® (Minneapolis, MN)⁹⁴ and Johnson & Johnson® (New Brunswick, NJ) – the latter partnering with Google® (Mountain View, CA) on a joint venture.⁹⁵ Both surgical robotic platforms are due for market release later in 2018.

In addition to those leading multinational medical device and technology corporations, the increasing demand for robotic surgery and its associated profitability make it an attractive area for venture capitalists and start-ups.⁹⁶ The market was worth more than \$3 billion in 2014 and is projected to exceed \$20 billion by 2021. Examples include Cambridge Medical Robotics (Cambridge, UK) with the Versius® surgical robotic system,⁹⁷ TransEnterix® (Morrisville, NC) with the Senhance™ multi-port and SurgiBot™ single-port robotic platforms,⁹⁸ and Titan Medical, Inc. (Toronto, ON) with the SPORT® robot.⁹⁹ As with the latest da Vinci® model (da Vinci® Single-Site®),¹⁰⁰ the aforementioned robotic systems are all single-port, which is an important feature when it comes to TORS.

Beyond novel surgical robots and procedures, there are a number of technologies that have been integrated with robotic surgery to enhance

surgical precision and improve patient safety. Augmented Reality (AR) is probably the most notable example, providing the surgeon with real-time navigational cues and representations of key anatomical structures that are overlaid on the operative field.¹⁰¹ Other future developments relate to miniaturisation of surgical robots that will further expand their application to paediatric patients with diseases of the head and neck.¹⁸ Finally, autonomous surgical robots are currently being trialed in the laboratory for a variety of high-precision procedures in ORL–HNS including mastoidectomy,¹⁰² cochlear implantation,¹⁰³ and the establishment of the translabyrinthine approach to the internal auditory canal to provide access for vestibular schwannoma resection.¹⁰⁴

Those phenomenal technological advances in less than a decade are unprecedented. With the rate at which technology is evolving, the only safe prediction is that robotics will continue to occupy an increasingly important role in ORL–HNS in the future. In the era of the Fourth Industrial Revolution, the surgical innovations that will emerge in the next decade are currently unimaginable.

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References

- Weinstein GS, O'Malley BW Jr, Hockstein NG. Transoral robotic surgery: supraglottic laryngectomy in a canine model. *Laryngoscope* 2005; **115**(7): 1,315–1,319.
- O'Malley BW Jr, Weinstein GS, Snyder W *et al*. Transoral robotic surgery (TORS) for base of tongue neoplasms. *Laryngoscope* 2006; **116**(8): 1,465–1,472.
- Vicini C, Dallan I, Canzi P *et al*. Transoral robotic tongue base resection in obstructive sleep apnoea-hypopnoea syndrome: a preliminary report. *ORL J Otorhinolaryngol Relat Spec* 2010; **72**(1): 22–27.
- Kang SW, Jeong JJ, Yun JS *et al*. Robot-assisted endoscopic surgery for thyroid cancer: experience with the first 100 patients. *Surg Endosc* 2009; **23**(11): 2,399–2,406.
- Tolley N, Arora A, Palazzo F *et al*. Robotic-assisted parathyroidectomy: a feasibility study. *Otolaryngol Head Neck Surg* 2011; **144**(6): 859–866.
- Terris DJ, Singer MC, Seybt MW. Robotic facelift thyroidectomy: II. *Clinical feasibility and safety*. *Laryngoscope* 2011; **121**(8): 1,636–1,641.
- Ansarin M, Zorzi S, Massaro MA *et al*. Transoral robotic surgery vs transoral laser microsurgery for resection of supraglottic cancer: a pilot surgery. *Int J Med Robot* 2014; **10**(1): 107–112.
- Van Abel KM, Moore EJ. The rise of transoral robotic surgery in the head and neck: emerging applications. *Expert Rev Anticancer Ther* 2012; **12**(3): 373–380.
- Weinstein GS, O'Malley BW Jr, Cohen MA *et al*. Transoral robotic surgery for advanced oropharyngeal carcinoma. *Arch Otolaryngol Head Neck Surg* 2010; **136**(11): 1,079–1,085.
- O'Malley BW Jr, Quon H, Leonhardt FD *et al*. Transoral robotic surgery for parapharyngeal space tumors. *ORL J Otorhinolaryngol Relat Spec* 2010; **72**(6): 332–336.
- Mendelsohn AH, Remacle M, Van Der Vorst S *et al*. Outcomes following transoral robotic surgery: supraglottic laryngectomy. *Laryngoscope* 2013; **123**(1): 208–214.
- Smith RV, Schiff BA, Sarta C *et al*. Transoral robotic total laryngectomy. *Laryngoscope* 2013; **123**(3): 678–682.
- Sims JR, Robinson NL, Moore EJ *et al*. Transoral robotic medial hypopharyngectomy: Surgical technique. *Head Neck* 2016; **38** Suppl 1: E2127–E2129.
- Mehta V, Johnson P, Tassler A *et al*. A new paradigm for the diagnosis and management of unknown primary tumors of the head and neck: a role for transoral robotic surgery. *Laryngoscope* 2013; **123**(1): 146–151.
- Arora A, Chaidas K, Garas G *et al*. Outcome of TORS to tongue base and epiglottis in patients with OSA intolerant of conventional treatment. *Sleep Breath* 2016; **20**(2): 739–747.
- Garas G, Kythreotou A, Georgalas C *et al*. Is transoral robotic surgery a safe and effective multilevel treatment for obstructive sleep apnoea in obese patients following failure of conventional treatment(s)? *Ann Med Surg (Lond)* 2017; **19**: 55–61.
- Georgalas C, Garas G, Hadjihannas E, Oostra A. Assessment of obstruction level and selection of patients for obstructive sleep apnoea surgery: an evidence-based approach. *J Laryngol Otol* 2010; **124**(1): 1–9.
- Erkul E, Duvvuri U, Mehta D *et al*. Transoral robotic surgery for the pediatric head and neck surgeries. *Eur Arch Otorhinolaryngol* 2017; **274**(3): 1,747–1,750.
- Selber JC. Transoral robotic reconstruction of oropharyngeal defects: a case series. *Plast Reconstr Surg* 2010; **126**(6): 1,978–1,987.
- Selber JC, Sarhane KA, Ibrahim AE *et al*. Transoral robotic reconstructive surgery. *Semin Plast Surg* 2014; **28**(1): 35–38.
- Tsang RK, Holsinger FC. Transoral endoscopic nasopharyngectomy with a flexible next-generation robotic surgical system. *Laryngoscope* 2016; **126**(10): 2,257–2,262.
- Chauvet D, Missistrano A, Hivelin M *et al*. Transoral robotic-assisted skull base surgery to approach the sella turcica: cadaveric study. *Neurosurg Rev* 2014; **37**(4): 609–617.
- Siegel R, Ma J, Zou Z *et al*. Cancer statistics 2014. *CA Cancer J Clin* 2014; **64**(1): 9–29.
- Marur S, D'Souza G, Westra WH *et al*. HPV-associated head and neck cancer: a virus-related cancer epidemic. *Lancet Oncol* 2010; **11**(8): 781–789.
- Badhey AK, Olson A, Kadakia S *et al*. Application of the Eighth Edition American Joint Committee on Cancer Staging System for HPV-Related Oropharyngeal Cancer Treated With Transoral Robotic Surgery. *Laryngoscope* 2017 [Epub ahead of print].
- Machtay M, Moughan J, Trotti A *et al*. Factors associated with severe late toxicity after concurrent chemoradiation for locally advanced head and neck cancer: an RTOG analysis. *J Clin Oncol* 2008; **26**(21): 3,582–3,589.
- Moorthy K, Munz Y, Dosis A *et al*. Dexterity enhancement with robotic surgery. *Surg Endosc* 2004; **18**(5): 790–795.
- Lorincz BB, Jowett N, Knecht R. Decision management in transoral robotic surgery: Indications, individual patient selection, and role in the multidisciplinary treatment for head and neck cancer from a European perspective. *Head Neck* 2016; **38** Suppl 1: E2190–E2196.
- Harris AT, Tanyi A, Hart RD *et al*. Transoral laser surgery for laryngeal carcinoma: has Steiner achieved a genuine paradigm shift in oncological surgery? *Ann R Coll Surg Engl* 2018; **100**(1): 2–5.
- Howard J, Masterson L, Dwivedi RC *et al*. Minimally invasive surgery versus radiotherapy/chemoradiotherapy for small-volume primary oropharyngeal carcinoma. *Cochrane Database Syst Rev* 2016; **12**: CD010963.
- Garas G, Ibrahim A, Ashrafian H *et al*. Evidence-based surgery: barriers, solutions, and the role of evidence synthesis. *World J Surg* 2012; **36**(8): 1,723–1,731.
- de Almeida JR, Byrd JK, Wu R *et al*. A systematic review of transoral robotic surgery and radiotherapy for early oropharynx cancer: a systematic review. *Laryngoscope* 2014; **124**(9): 2,096–2,102.
- Paleri V, Fox H, Coward S *et al*. Transoral robotic surgery for residual and recurrent oropharyngeal cancers: Exploratory study of surgical innovation using the IDEAL framework for early-phase surgical studies. *Head Neck* 2018; **40**(3): 512–525.
- Owaddally W, Hurt C, Timmins H *et al*. PATHOS: a phase II/III trial of risk-stratified, reduced intensity adjuvant treatment in patients undergoing transoral surgery for Human papillomavirus (HPV) positive oropharyngeal cancer. *BMC Cancer* 2015; **15**: 602.
- Holsinger FC, Ferris RL. Transoral Endoscopic Head and Neck Surgery and Its Role Within the Multidisciplinary Treatment Paradigm of Oropharynx Cancer: Robotics, Lasers, and Clinical Trials. *J Clin Oncol* 2015; **33**(29): 3,285–3,292.
- Nichols AC, Yoo J, Hammond JA *et al*. Early-stage squamous cell carcinoma of the oropharynx: radiotherapy vs. *trans-oral robotic surgery (ORATOR)-study protocol for a randomized phase II trial*. *BMC Cancer* 2013; **13**: 133.

37. Bekeny JR, Ozer E. Transoral robotic surgery frontiers. *World J Otorhinolaryngol Head Neck Surg* 2016; **2(2)**: 130–135.
38. Grant DG, Salassa JR, Hinni ML *et al.* Transoral laser microsurgery for carcinoma of the supraglottic larynx. *Otolaryngol Head Neck Surg* 2007; **136(6)**: 900–906.
39. Arora A, Kotecha J, Acharya A *et al.* Determination of biometric measures to evaluate patient suitability for transoral robotic surgery. *Head Neck* 2015; **37(9)**: 1,254–1,260.
40. Olsen SM, Moore EJ, Koch CA *et al.* Transoral robotic surgery for supraglottic squamous cell carcinoma. *Am J Otolaryngol* 2012; **33(4)**: 379–384.
41. Forastiere AA, Ismaila N, Lewin JS *et al.* Use of Larynx–Preservation Strategies in the Treatment of Laryngeal Cancer: American Society of Clinical Oncology Clinical Practice Guideline Update. *J Clin Oncol* 2017 [Epub ahead of print].
42. Forastiere AA, Weber RS, Trotti A. Organ Preservation for Advanced Larynx Cancer: Issues and Outcomes. *J Clin Oncol* 2015; **33(29)**: 3,262–3,268.
43. Nguyen NP, Moltz CC, Frank C *et al.* Dysphagia following chemoradiation for locally advanced head and neck cancer. *Ann Oncol* 2004; **15(3)**: 383–388.
44. Lawson G, Mendelsohn AH, Van Der Vorst S *et al.* Transoral robotic surgery total laryngectomy. *Laryngoscope* 2013; **123(1)**: 193–196.
45. Dowthwaite S, Nichols AC, Yoo J *et al.* Transoral robotic total laryngectomy: report of 3 cases. *Head Neck* 2013; **35(11)**: E338–E342.
46. Sayles M, Grant DG. Preventing pharyngo–cutaneous fistula in total laryngectomy: a systematic review and meta–analysis. *Laryngoscope* 2014; **124(5)**: 1,150–1,163.
47. Krishnan G, Krishnan S. Transoral Robotic Surgery Total Laryngectomy: Evaluation of Functional and Survival Outcomes in a Retrospective Case Series at a Single Institution. *ORL J Otorhinolaryngol Relat Spec* 2017; **79(4)**: 191–201.
48. Galer CE, Kies MS. Evaluation and management of the unknown primary carcinoma of the head and neck. *J Natl Compr Canc Netw* 2008; **6(10)**: 1,068–1,075.
49. Richards TM, Bhide SA, Miah AB *et al.* Total Mucosal Irradiation with Intensity–modulated Radiotherapy in Patients with Head and Neck Carcinoma of Unknown Primary: A Pooled Analysis of Two Prospective Studies. *Clin Oncol (R Coll Radiol)* 2016; **28(9)**: e77–e84.
50. Hatten KM, O'Malley BW Jr, Bur AM *et al.* Transoral Robotic Surgery–Assisted Endoscopy With Primary Site Detection and Treatment in Occult Mucosal Primaries. *JAMA Otolaryngol Head Neck Surg* 2017; **143(3)**: 267–273.
51. Krishnan S, Connell J, Ofo E. Transoral robotic surgery base of tongue mucosectomy for head and neck cancer of unknown primary. *ANZ J Surg* 2017; **87(12)**: E281–E284.
52. Winter SC, Ofo E, Meikle D *et al.* Trans–oral robotic assisted tongue base mucosectomy for investigation of cancer of unknown primary in the head and neck region. *The UK experience. Clin Otolaryngol* 2017; **42(6)**: 1,247–1,251.
53. Durmus K, Rangarajan SV, Old MO *et al.* Transoral robotic approach to carcinoma of unknown primary. *Head Neck* 2014; **36(6)**: 848–852.
54. Huang SH, O'Sullivan B. Overview of the 8th Edition TNM Classification for Head and Neck Cancer. *Curr Treat Options Oncol* 2017; **18(7)**: 40.
55. NICE Guideline. *Cancer of the upper aerodigestive tract: assessment and management in people aged 16 and over.* National Institute for Health and Care Excellence, 2016; London, United Kingdom.
56. U.S. Preventative Services Task Force, Bibbins–Domingo K, Grossman DC *et al.* Screening for obstructive sleep apnea in adults: US preventive services task force recommendation statement. *JAMA* 2017; **317(4)**: 407–414.
57. Cho WS, Garas G, Morgan A, Chaurasia M. Patient compliance to continuous positive airway pressure (CPAP) therapy for sleep apnoea: a completed audit cycle. *Ir J Med Sci* 2013; **182**: S509–S531.
58. Bradley TD, Floras JS. Obstructive sleep apnoea and its cardiovascular consequences. *Lancet* 2009; **373(9657)**: 82–93.
59. Meccariello G, Cammaroto G, Montevecchi F *et al.* Transoral robotic surgery for the management of obstructive sleep apnea: a systematic review and meta–analysis. *Eur Arch Otorhinolaryngol* 2017; **274(2)**: 647–653.
60. Chiffer RC, Schwab RJ, Keenan BT *et al.* Volumetric MRI analysis pre– and post–Transoral robotic surgery for obstructive sleep apnea. *Laryngoscope* 2015; **125(8)**: 1,988–1,995.
61. Miller SC, Nguyen SA, Ong AA *et al.* Transoral robotic base of tongue reduction for obstructive sleep apnea: A systematic review and meta–analysis. *Laryngoscope* 2017; **127(1)**: 258–265.
62. Ratneswaran C, Sagoo MK, Steier J. Preface for the 3rd Clinical Update Sleep, 23rd February 2018, Royal College of Physicians, London, UK: year in review. *J Thorac Dis* 2018 [Epub ahead of print].
63. Garas G, Jarra O, Tolley N *et al.* Is there survival benefit from life–long follow–up after treatment for differentiated thyroid cancer? *Int J Surg* 2013; **11(2)**: 116–121.
64. Arora A, Swords C, Garas G *et al.* The perception of scar cosmesis following thyroid and parathyroid surgery: A prospective cohort study. *Int J Surg* 2016; **25**: 38–43.
65. Tan CT, Cheah WK, Delbridge L. “Scarless” (in the neck) endoscopic thyroidectomy (SET): an evidence–based review of published techniques. *World J Surg* 2008; **32(7)**: 1,349–1,357.
66. Christakis I, Constantinides V, Garas G *et al.* Minimally Invasive Endocrine (Thyroid, Parathyroid, Adrenal) Surgery: Evolution of Operative Techniques, Safety, Effectiveness and Outcomes. In: Hawthorne FT, ed. *Minimally Invasive Surgery: Evolution of Operative Techniques, Safety and Effectiveness and Long–Term Clinical Outcomes.* New York, USA: Nova Science Publishers 2014: 1–66.
67. Kim MJ, Nam KH, Lee SG *et al.* Yonsei Experience of 5000 Gasless Transaxillary Robotic Thyroidectomies. *World J Surg* 2018; **42(2)**: 393–401.
68. Garas G, Cingolani I, Panzarasa P *et al.* Network analysis of surgical innovation: Measuring value and the virality of diffusion in robotic surgery. *PLoS One* 2017; **12(8)**: e0183332.
69. Arora A, Garas G, Sharma S *et al.* Comparing transaxillary robotic thyroidectomy with conventional surgery in a UK population: A case control study. *Int J Surg* 2016; **27**: 110–117.
70. Cabot JC, Lee CR, Brunaud L *et al.* Robotic and endoscopic transaxillary thyroidectomies may be cost prohibitive when compared to standard cervical thyroidectomy: a cost analysis. *Surgery* 2012; **152(6)**: 1,016–1,024.
71. Duh QY. Robot–assisted endoscopic

- thyroidectomy: has the time come to abandon neck incisions? *Ann Surg* 2011; **253(6)**: 1,067–1,068.
72. Lin HS. Response to: "Robotic thyroidectomy: Seoul is not Varese" by Dr Dionigi. *Otolaryngol Head Neck Surg* 2013; **148(1)**: 179.
73. Lee S, Park S, Lee CR *et al*. The impact of body habitus on the surgical outcomes of transaxillary single-incision robotic thyroidectomy in papillary thyroid carcinoma patients. *Surg Endosc* 2013; **27(7)**: 2,407–2,414.
74. Alkan U, Zarchi O, Rabinovics N *et al*. The cause of brachial plexopathy in robot-assisted transaxillary thyroidectomy—A neurophysiological investigation. *Laryngoscope* 2016; **126(9)**: 2,187–2,193.
75. Luginbuhl A, Schwartz DM, Sestokas AK *et al*. Detection of evolving injury to the brachial plexus during transaxillary robotic thyroidectomy. *Laryngoscope* 2012; **122(1)**: 110–115.
76. FDA. *Medical Device Class II Recall Silver Spring, MD2011*. [Available from: <http://www.fda.gov/ICECI/EnforcementActions/WarningLetters/2013/ucm363260.html> (cited March 2018).].
77. Garas G, Poulasouchidou M, Dimoulas A *et al*. Radiological considerations and surgical planning in the treatment of giant parathyroid adenomas. *Ann R Coll Surg Engl* 2015; **97(4)**: e64–e66.
78. Noureldine SI, Jackson NR, Tufano RP *et al*. A comparative North American experience of robotic thyroidectomy in a thyroid cancer population. *Langenbecks Arch Surg* 2013; **398(8)**: 1,069–1,074.
79. Piccoli M, Mullineris B, Santi D *et al*. Advances in Robotic Transaxillary Thyroidectomy in Europe. *Curr Surg Rep* 2017; **5(8)**: 17.
80. Bomeli SR, Duke WS, Terris DJ. Robotic facelift thyroid surgery. *Gland Surg* 2015; **4(5)**: 403–409.
81. Kim HY, Chai YJ, Dionigi G *et al*. Transoral robotic thyroidectomy: lessons learned from an initial consecutive series of 24 patients. *Surg Endosc* 2018; **32(2)**: 688–694.
82. Tolley N, Garas G, Palazzo F *et al*. Long-term prospective evaluation comparing robotic parathyroidectomy with minimally invasive open parathyroidectomy for primary hyperparathyroidism. *Head Neck* 2016; **38** Suppl 1: E300–E306.
83. Malik HT, Marti J, Darzi A, Mossialos E *et al*. Savings from reducing low – value general surgical interventions. *Br J Surg* 2018; **105(1)**: 13–25.
84. Wong KA, Hodgson L, Garas G *et al*. How can cardiothoracic and vascular medical devices stay in the market? *Interact Cardiovasc Thorac Surg* 2016; **23(6)**: 940–948.
85. Remacle M, Prasad VMN, Lawson G *et al*. Transoral robotic surgery (TORS) with the Medrobotics Flex System: first surgical application on humans. *Eur Arch Otorhinolaryngol* 2015; **272(6)**: 1,451–1,455.
86. Mattheis S, Hasskamp P, Holtmann L *et al*. Flex Robotic System in transoral robotic surgery: The first 40 patients. *Head Neck* 2017; **39(3)**: 471–475.
87. Friedrich DT, Scheithauer MO, Greve J *et al*. Application of a computer-assisted flexible endoscope system for transoral surgery of the hypopharynx and upper esophagus. *Eur Arch Otorhinolaryngol* 2017; **274(5)**: 2,287–2,293.
88. Schuler PJ, Hoffmann TK, Duvvuri U *et al*. Demonstration of nasopharyngeal surgery with a single port operator-controlled flexible endoscope system. *Head Neck* 2016; **38(3)**: 370–374.
89. Remacle M, Prasad VMN. Preliminary experience in transoral laryngeal surgery with a flexible robotic system for benign lesions of the vocal folds. *Eur Arch Otorhinolaryngol* 2018; **275(3)**: 761–765.
90. Tan Wen Sheng B, Wong P, Teo Ee Hoon C. Transoral robotic excision of laryngeal papillomas with Flex(R) Robotic System – A novel surgical approach. *Am J Otolaryngol* 2018 [Epub ahead of print].
91. Mattheis S, Lang S. A new flexible endoscopy-system for the transoral resection of head and neck tumors. *Laryngorhinootologie* 2015; **94(1)**: 25–28.
92. Flex® Robotic System (Medrobotics® Inc.) Raynham, MA 2018. [Available from: <http://medrobotics.com> (cited March 2018).].
93. New surgical robots are about to enter the operating theatre. *The Economist*. 2017; London, United Kingdom.
94. Medtronic I. Mazor X™ robotic guidance system Minneapolis, MN 2018. [Available from: <http://www.medtronic.com/us-en/healthcare-professionals/products/neurological/spine-robotics/mazorx.html> (cited March 2018).].
95. JNJ Innovation. Google, J&J Partner to Advance Surgical Robotics New Brunswick, NJ 2018. [Available from: <https://www.jnjinnovation.com/google-jj-partner-advance-surgical-robotics> (cited March 2018).].
96. WinterGreen Research Report Lexington, MA, 2014.
97. Cambridge Medical Robotics. Introducing Versius Cambridge, United Kingdom 2018. [Available from: <https://cmrsurgical.com> (cited March 2018).].
98. TransEnterix® Morrisville, NC 2018 [Available from: <https://www.transenterix.com>].
99. Titan Medical Inc. SPORT® robot Toronto, ON 2018 [Available from: <https://titanmedicalinc.com>].
100. Intuitive Surgical® Inc. da Vinci® Single-Site® Sunnyvale, CA 2018 [Available from: https://www.intuitivesurgical.com/products/davinci_surgical_system/da-vinci-single-site/ (cited March 2018).].
101. Liu WP, Richmon JD, Sorger JM *et al*. Augmented reality and cone beam CT guidance for transoral robotic surgery. *J Robot Surg* 2015; **9(3)**: 223–233.
102. Yoo MH, Lee HS, Yang CJ *et al*. A cadaver study of mastoidectomy using an image-guided human-robot collaborative control system. *Laryngoscope Investig Otolaryngol* 2017; **2(5)**: 208–214.
103. Caversaccio M, Gavaghan K, Wimmer W *et al*. Robotic cochlear implantation: surgical procedure and first clinical experience. *Acta Otolaryngol* 2017; **137(4)**: 447–454.
104. Dillon NP, Balachandran R, Siebold MA *et al*. Cadaveric Testing of Robot-Assisted Access to the Internal Auditory Canal for Vestibular Schwannoma Removal. *Otol Neurotol* 2017; **38(3)**: 441–447.