

Review

Transoral Robotic Surgery in the Treatment of Head and Neck Cancer: Application and Prospect

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Abstract: Transoral robotic surgery (TORS) has reshaped the surgical management of head and neck neoplasms since its introduction in the mid-2000s, offering a minimally invasive transoral route to lesions of the oropharynx, larynx, hypopharynx, and nasopharynx. This narrative review synthesizes the technical foundations, current clinical evidence, and emerging directions of TORS, with explicit attention to study rigor and evidentiary hierarchy. Powered by the da Vinci platform, TORS provides magnified three-dimensional visualization and wristed instrumentation that enable en bloc resection with reduced external morbidity, shorter hospitalization, and the potential to spare or de-intensify adjuvant radiotherapy in selected human papillomavirus (HPV)-driven oropharyngeal cancers. For early-stage oropharyngeal disease, local control rates of 90–95% and disease-specific survival above 90% are consistently reported, and recent systematic reviews and large multicenter cohorts, including the international Recurrent Tumors of the Upper Aerodigestive Tract (RECUT) experience, confirm durable oncologic and functional outcomes in both primary and salvage settings, although randomized trials have yielded nuanced, sometimes divergent quality-of-life results. We appraise outcomes by anatomical subsite, the de-escalation trial landscape, complications and their mitigation, learning-curve dynamics, health economics, and the rapidly evolving integration of artificial intelligence in segmentation, augmented-reality navigation, intraoperative margin assessment, and outcome prediction. Recent evidence confirms that TORS is a valuable but expertise-dependent option whose benefit is greatest in carefully selected patients managed within multidisciplinary, high-volume pathways. We conclude by defining the principal unresolved questions and the evidence required to position TORS appropriately within contemporary multidisciplinary care.

Keywords: Transoral Robotic Surgery; Head and Neck Cancer; Oropharyngeal Carcinoma; Human Papillomavirus; Minimally Invasive Surgery; Surgical Robotics; Artificial Intelligence; De-Escalation Therapy

1. Introduction

Over the last twenty years, the surgical treatment of head and neck malignancies has undergone a pronounced transformation, propelled by two concurrent shifts: first, a surge in human papillomavirus (HPV)-related oropharyngeal squamous cell carcinoma (OPSCC) among younger individuals whose prognosis tends to be favorable; and second, the coming-of-age of minimally invasive operative techniques [1,2]. Within this landscape, transoral robotic surgery (TORS)—initially reported by O'Malley, Weinstein, and co-workers between 2006 and 2007 for oropharyngeal and supraglottic neoplasms—has steadily moved to the forefront [3]. Harnessing the da Vinci system (Intuitive

Surgical, Sunnyvale, CA), TORS reaches deeply situated upper aerodigestive tract lesions through the mouth, obviating external incisions or mandibulotomy and, in principle, cutting surgical morbidity while preserving oncologic soundness [4]. Nearly two decades of accumulated experience, now summarized in contemporary reviews, has progressively refined both the indications and the technical execution of the procedure [5].

From its earliest description onward, TORS has found application across a widening array of head and neck subsites: the oropharynx (tonsil and tongue base), supraglottic larynx, hypopharynx, nasopharynx, and parapharyngeal space [6–8]. Advocates contend that TORS holds advantages over both conventional open surgery and definitive (chemo)radiotherapy—briefer hospitalizations, faster reinstitution of oral intake, less reliance on tracheostomy and gastrostomy tubes, and better preservation of swallowing and voice [9,10]. For HPV-associated OPSCC specifically, TORS has been cast as a linchpin of treatment de-escalation: surgical excision may allow adjuvant radiation or chemotherapy to be reduced or withdrawn altogether, thereby lessening late toxicity in patients likely to survive for many decades [11,12].

For all these encouraging trends, TORS's place in modern head and neck oncology remains a matter of vigorous debate. Detractors highlight the scarcity of high-grade randomized evidence, selection bias inherent in large database analyses, and the possibility that surgical pathology may upstage disease and—paradoxically—amplify rather than shrink the adjuvant treatment burden [13,14]. The ORATOR trial, among the handful of randomized comparisons pitting TORS against primary radiotherapy for oropharyngeal cancer, found that radiotherapy actually produced better swallowing-related quality of life at twelve months, with the two arms converging only later—a result that undermines blanket claims of functional superiority [15]. Moreover, ORATOR2 was halted prematurely after unexpected treatment-related deaths emerged in the transoral surgery arm, a reminder that grave adverse events can occur even at seasoned centers [16].

Alongside these clinical advances, artificial intelligence (AI) and machine learning have attracted considerable attention throughout surgical oncology, with proposed uses spanning preoperative tumor delineation and outcome forecasting, intraoperative guidance, and automated appraisal of surgical skill [17,18]. Although these technologies carry theoretical potential to sharpen TORS precision and safety, the actual evidence for AI integration specifically within TORS workflows is still in its infancy; much of the published literature rests on extrapolation from other surgical specialties rather than on direct, TORS-specific validation.

A number of earlier narrative reviews have recapitulated the technical fundamentals and initial clinical experience with TORS [4,19,20]. What has been missing is a thorough, critically appraised synthesis that weaves together the newest randomized trial data, systematically tackles lingering controversies, quantifies learning-curve parameters, weighs health-economic evidence, and rigorously audits where AI applications in TORS actually stand—all while paying explicit attention to evidentiary tier and study quality. This review endeavors to close that gap by offering an up-to-date, evidence-grounded analysis of TORS in head and neck cancer, delineating both its established clinical roles and domains where the evidence remains thin.

2. Review Methodology

This narrative review is underpinned by a structured search of the PubMed, MEDLINE, and Cochrane Library databases. The search was initially conducted in March 2026 and updated in September 2026 during revision, and spans publications from January 2007, shortly after the first clinical reports of TORS, through the search date. Search terms combined ‘transoral robotic surgery’ and ‘TORS’ with ‘head and neck cancer,’ ‘oropharyngeal,’ ‘laryngeal,’ ‘hypopharyngeal,’ ‘complications,’ ‘learning curve,’ ‘cost-effectiveness,’ and ‘artificial intelligence.’ No language restrictions were imposed.

2.1. Inclusion and Exclusion Criteria

Eligible studies were those reporting clinical outcomes, safety profiles, technical aspects, health-economic data, or technological applications of TORS for malignant head and neck pathology. Both English-language and non-English publications with available abstracts were considered. Studies were excluded if they focused exclusively on benign disease without malignant comparators, if they were conference abstracts without full-text availability, or if they reported duplicate data from an already included series. Priority was given to randomized controlled trials, systematic reviews, and large multi-institutional cohorts; small case series were included only when no higher-level

evidence existed for a given indication.

2.2. Evidence Level Assessment

Where applicable, incorporated studies were stratified by evidentiary tier using a modified version of the Oxford Centre for Evidence-Based Medicine hierarchy:

Level 1: Systematic reviews of randomized controlled trials (RCTs) or individual RCTs.

Level 2: Systematic reviews of cohort studies or individual prospective cohort investigations.

Level 3: Retrospective cohort studies, case-control investigations, or large database analyses.

Level 4: Case series and cross-sectional investigations.

Level 5: Case reports, expert opinion, and preclinical studies.

For AI-related sections, an additional layer of classification was applied, distinguishing between studies validated directly in TORS procedures, those validated in broader head and neck cancer surgery but not TORS specifically, preclinical or animal/cadaveric investigations, and work extrapolated from unrelated surgical disciplines.

2.3. Search Results

The initial search returned 487 records. After deduplication and title/abstract screening, 92 full-text articles underwent eligibility assessment. Following full-text review, 58 studies were incorporated into the qualitative synthesis, and further references were identified through citation chasing and hand-searching of reference lists. In response to peer review, the search was updated through September 2026 to strengthen coverage of the most recent five years, adding contemporary randomized and comparative trials, systematic reviews, large multicenter cohorts, and health-economic and artificial-intelligence studies. After exclusion of duplicate, outdated, and non-relevant entries, 105 unique references are cited in the final manuscript; 53 (50.5%) were published in 2022–2026 and 30 (28.6%) in 2023–2026.

3. Technical Foundations of TORS

3.1. Robotic Platform and Instrumentation

The da Vinci surgical system consists of three core elements: a surgeon console, a patient-side cart mounting robotic arms, and a high-definition three-dimensional (3D) endoscopic optical system [3]. The surgeon operates from an immersive console, viewing a magnified stereoscopic image of the operative field while manipulating hand controls that translate wrist and finger movements into precise actions of the robotic instruments inside the patient. Motion scaling and tremor filtration further enhance precision.

For TORS cases, the patient-side cart is stationed at the head of the operating table, and two or three robotic arms are introduced through the mouth alongside a 0° or 30° endoscope [21]. The articulating EndoWrist instruments—including Maryland dissectors, cautery devices, and retractors—offer seven degrees of freedom and 540° rotation, enabling dissection in confined oropharyngeal and laryngeal spaces that would be difficult to access with rigid straight instruments.

3.2. Setup and Procedural Workflow

TORS cases demand a methodical setup sequence encompassing patient positioning, oral cavity exposure, robot docking, and instrument calibration. Early series documented appreciable setup times, with average room preparation and docking intervals surpassing 30 min; as institutional experience has grown, however, these intervals have shortened considerably, and seasoned centers now report total robotic setup times under 15 min for routine cases [22,23].

The standard oncologic TORS operation follows several key phases: exposure and diagnostic inspection of the tumor and surrounding anatomy; circumferential mucosal incision; deep dissection along appropriate tissue planes; en bloc tumor removal with attention to margin adequacy; hemostasis; and, when indicated, concurrent or staged neck dissection. Specimen orientation and immediate frozen-section margin assessment are frequently employed to guide the extent of resection.

3.3. Patient Selection and Contraindications

Careful patient selection is indispensable for safe and effective TORS. Favorable factors include adequate mouth opening (typically an interincisor distance exceeding 3 cm), advantageous mandibular anatomy, tumors accessible transorally without excessive retraction, and favorable overall health status. Preoperative imaging—principally contrast-enhanced CT and/or MRI—is essential for delineating tumor extent, identifying vascular anomalies such as medialized retropharyngeal carotid arteries, and planning the surgical approach [24].

Historically, several conditions were regarded as absolute contraindications, encompassing prior radiotherapy to the region, retropharyngeal carotid artery medialization, trismus, and advanced T4 disease [25]. With growing experience, however, many of these have shifted from absolute to relative contraindications. Salvage TORS after radiotherapy is now performed at specialized centers, albeit with elevated bleeding risk [26]. Patients with medialized retropharyngeal carotids can be managed with preoperative vascular mapping and, in selected cases, microvascular flap coverage [27]. Advanced T3 and select T4a lesions may be considered in experienced hands when complete resection is achievable and reconstruction is available.

4. Clinical Evidence and Controversies

4.1. Oncologic Outcomes

The oncologic effectiveness of TORS has been gauged chiefly through retrospective single-institution and multi-institutional cohort investigations. For early-stage (T1–T2) oropharyngeal squamous cell carcinoma (OPSCC), reported local control rates consistently fall in the 90–95% range, with disease-specific survival exceeding 90% in most series [9,10]. A multi-institutional analysis of 410 patients by de Almeida and colleagues reported 2-year locoregional control of 91.8%, disease-specific survival of 94.5%, and overall survival of 91% [10].

National Cancer Database (NCDB) analyses, which encompass thousands of patients, have linked TORS to survival outcomes comparable to both open surgery and primary radiotherapy for early-stage OPSCC [28,29]. These database investigations carry important limitations inherent to retrospective administrative data, however. Patients selected for TORS likely possess more favorable tumor characteristics and better performance status than those undergoing open surgery or definitive chemoradiation, introducing selection bias. NCDB data also lack granular information on HPV/p16 status, functional outcomes, and quality-of-life metrics, limiting the depth of interpretation [13]. Comparisons of upfront surgery and intensity-modulated radiotherapy in HPV-positive disease likewise report comparable survival in modern real-world cohorts, with treatment choice increasingly driven by functional toxicity and patient preference rather than survival differences [30,31]. A consecutive single-institution study from a tertiary center in Eastern Denmark documented excellent oncologic outcomes after TORS with low rates of adjuvant treatment in carefully selected early-stage disease [32], and contemporary reviews continue to place local control in the 90–95% range across oropharyngeal and selected hypopharyngeal primaries [33].

Achieving clear surgical margins is a central determinant of oncologic outcomes after TORS, as positive or close margins trigger adjuvant therapy and may compromise local control. Reported positive-margin rates range from approximately 5% to 20%, varying by subsite, T classification, and surgeon experience, and base-of-tongue tumors consistently show higher positive-margin rates than tonsillar tumors in pooled analyses, although this difference has not translated into higher recurrence [34]. Intraoperative frozen-section control has been associated with improved final margin status in HPV-positive OPSCC [35], and multidisciplinary tumor board review reclassifies a meaningful proportion of initially positive or close margins, in some cases altering adjuvant treatment decisions [36]. Margin status also retains prognostic weight when TORS is combined with neck dissection [37]. Despite these refinements, the definition and prognostic threshold of a “close” margin after transoral resection remain debated, and standardized reporting is still lacking [38].

Level of evidence: Level 3 for most oncologic outcome data; Level 1 limited to the ORATOR and ORATOR2 trials (small sample sizes, early termination for ORATOR2).

4.2. Functional Outcomes and Quality of Life

Functional outcomes rank among the most frequently cited merits of TORS. Reported benefits include earlier reinstatement of oral diet—typically within 24–48 h for uncomplicated cases—low rates of prolonged gastrostomy tube dependence, and preservation of swallowing and speech function [6]. A prospective series of 81 OPSCC pa-

tients found that all were discharged on a full oral diet without nasogastric tube feeding, with gastrostomy tube rates of 24% at 6 months and 9% at 12 months, while Head and Neck Cancer Inventory scores showed an initial postoperative decline followed by partial recovery by 12 months [6]. A prospective non-randomized controlled study comparing 30 TORS patients with 26 concurrent chemoradiotherapy patients found that TORS was associated with better short-term eating and diet scores in the early post-treatment period, although the TORS group returned to baseline whereas the CRT group continued to show lower diet and functional oral intake scores at 12 months [39]. A recent systematic review pooling 28 studies and 1,541 patients found that speech and swallowing generally recovered toward baseline within months after TORS for OPSCC, although recovery was slower after tongue base resection and in patients who received adjuvant radiotherapy [40].

The functional-benefit narrative is more nuanced than often presented, however. The ORATOR trial, a randomized phase II study comparing TORS plus adjuvant therapy as indicated versus primary (chemo)radiotherapy for T1–T2 N0–N2 OPSCC, found that radiotherapy actually yielded superior swallowing-related quality of life at 12 months, as measured by the MD Anderson Dysphagia Inventory (MDADI) [15]. By 5 years, the two arms had converged, with no significant differences in swallowing or global quality of life [41].

The ORATOR2 trial, a randomized comparison of de-escalated radiotherapy versus transoral robotic surgery with or without reduced-dose adjuvant radiotherapy for HPV-associated OPSCC, similarly reported mixed functional results, with no significant difference in swallowing-related quality of life at 1 year between treatment arms. The trial was terminated early due to unexpected treatment-related mortality in the surgery arm, underscoring that TORS is not without serious risks even in experienced hands [16]. Long-term functional data from ORATOR2 remain limited due to early termination. Beyond the randomized trials, a study of 84 patients undergoing transoral surgery for oropharyngeal, hypopharyngeal, and supraglottic lesions identified poor performance status, prior neck irradiation, and longer operative time as independent predictors of postoperative dysphagia, reinforcing that functional outcomes depend heavily on patient and treatment factors rather than the surgical approach alone [42].

The presumption that TORS universally confers superior functional outcomes is not borne out by the limited randomized evidence. Benefits appear to be domain-specific and time-dependent, with trade-offs between acute surgical morbidity and late radiation toxicity. Patient preferences regarding acute versus late toxicity, treatment duration, and the desire to avoid radiotherapy should inform shared decision-making.

4.3. Transoral Surgery versus Primary Radiotherapy: The Ongoing Debate

The choice between transoral surgery (including TORS) and primary (chemo)radiotherapy for early-stage HPV-associated OPSCC stands as one of the most vigorously contested topics in contemporary head and neck oncology. Both approaches achieve excellent oncologic control in early-stage disease, but they differ substantially in their toxicity profiles, treatment trajectories, and long-term functional implications.

Primary (chemo)radiotherapy is associated with well-characterized acute toxicities including mucositis, dermatitis, dysphagia, weight loss, and fatigue, typically peaking during the third to fifth weeks of treatment [43]. These acute effects generally resolve within weeks to months after completion, although some patients experience persistent dysphagia or xerostomia. Treatment duration is typically 6–7 weeks for definitive radiotherapy or chemoradiotherapy.

Long-term outcomes diverge more substantially. Radiotherapy-related late toxicities encompass permanent xerostomia, dental caries, soft tissue fibrosis, trismus, osteoradionecrosis, and persistent dysphagia, which can emerge months to years after treatment and may be progressive [44]. TORS, by contrast, avoids these radiation-specific late effects but carries its own acute surgical morbidity: postoperative pain, bleeding risk, temporary swallowing difficulty, and, in some cases, the need for temporary gastrostomy or tracheostomy.

Patient-reported quality of life data from randomized trials remain limited and inconsistent. The ORATOR trial found RT superior at one year for swallowing-related QoL but equivalent by five years [15]. Observational studies have reported varying results depending on the specific instruments used and the timing of assessment. Importantly, quality-of-life benefits of TORS appear most pronounced in patients who ultimately do not require adjuvant therapy; for those who proceed to adjuvant CRT, the functional advantage largely disappears [45]. Real-world database analyses have suggested lower gastrostomy tube rates with TORS compared with non-robotic surgery, but these findings are subject to selection bias [29]. The decision is further complicated by the fact that many TORS patients ultimately require adjuvant radiotherapy, thereby incurring toxicities of both modalities.

A central concern with primary TORS is the potential for pathologic upstaging to increase rather than decrease the intensity of adjuvant therapy. Surgical resection may uncover high-risk features such as positive margins, extracapsular extension (ECE), or multiple positive lymph nodes that were not appreciated preoperatively, thereby converting a planned de-escalation approach into standard dual-modality or even triple-modality treatment. The risk of upstaging is particularly relevant for patients with clinically node-positive disease or larger primary tumors.

This risk underscores the importance of careful patient selection and risk stratification. De-escalation strategies employing TORS should ideally be restricted to clinical trial protocols or to patients with a high pretest probability of low-risk pathologic findings. **Table 1** summarizes the key randomized and comparative trials of TORS in oropharyngeal cancer discussed in this section.

Table 1. Summary of Key Randomized and Comparative Trials of TORS in Oropharyngeal Cancer.

Trial/Study	Design	Population	Key Findings	Evidence Level
ORATOR [15]	Randomized phase II	T1–T2 OPSCC, N0–N2	RT superior at 1yr for swallowing QoL; equivalent by 5yr	Level 1
ORATOR2 [16]	Randomized phase II	HPV+ OPSCC, T1–T2, N0–N2	De-escalated RT vs. TORS±reduced RT; mixed functional results	Level 1
ECOG 3311 [46]	Randomized phase II	p16+ locally advanced OPSCC	2yr PFS 96.9% observation, 94.9% 50Gy, 96.0% 60Gy	Level 1
PATHOS [47]	Randomized phase II/III	HPV+ OPSCC after TORS	Risk-stratified adjuvant de-escalation; phase II complete, III ongoing	Level 1–2
NCDB Analysis [28]	Retrospective database	Early-stage OPSCC	TORS associated with improved survival vs. non-robotic surgery	Level 3
MarketScan [29]	Retrospective database	Surgically treated OPC	TORS associated with lower costs and lower gastrostomy/tracheostomy rates vs. non-robotic surgery	Level 3

4.4. Complications and Safety Profile

TORS is generally associated with a favorable safety profile, but serious and potentially life-threatening complications do occur. The most commonly reported complications include postoperative bleeding, infection, dysphagia, and injury to adjacent structures such as teeth or the hypoglossal nerve [48,49]. Complication rates vary considerably across series, reflecting differences in case mix, surgeon experience, and definitions of complications.

Postoperative bleeding is the most significant acute complication and the leading cause of readmission after TORS. Reported rates range from 3.1% to 13.2% across series, with substantial variability driven by case mix and definitions [50]. A meta-analysis by Stokes and colleagues reported an overall postoperative hemorrhage rate of 6.47%, with major bleeding requiring transfusion or reoperation occurring in 2.90% of cases [50]. Bleeding typically occurs between postoperative days 5 and 10, corresponding to the period of eschar separation. Subsite-specific pooled data indicate that postoperative hemorrhage rates are similar between tonsillar and base-of-tongue resections [34].

While the overall bleeding rate is modest, the most feared complication is catastrophic hemorrhage from carotid artery injury or blowout. This rare but potentially fatal event is particularly relevant in salvage TORS after radiotherapy, where tissue planes are distorted and vascular structures may be less well protected. Patients with medialized retropharyngeal carotid arteries are also at elevated risk. The incidence of carotid artery injury during TORS is low, but the mortality rate when it occurs is high.

Prophylactic external carotid artery (ECA) ligation has been proposed as a strategy to reduce the risk of severe postoperative bleeding. A study of 201 OPSCC patients undergoing TORS found that while overall bleeding rates did not differ significantly between patients with (5.8%) and without (6.7%) prophylactic ECA ligation ($P = 0.53$), all cases of severe or life-threatening bleeding occurred exclusively in the non-ligation group [51]. These data suggest that ECA ligation may not reduce overall bleeding incidence but could mitigate the risk of catastrophic hemorrhage. For lateralized primaries, lymphatic mapping with SPECT-CT has been used to guide selective neck management, with very low contralateral neck failure after ipsilateral treatment [52].

For patients with radiographically confirmed retropharyngeal carotid arteries, once considered an absolute contraindication to TORS, specialized centers have demonstrated feasibility using careful preoperative vascular mapping, intraoperative navigation, and, when necessary, microvascular flap coverage to protect the exposed vessel [27]. This approach requires substantial surgical expertise and should only be attempted at high-volume centers with reconstructive capabilities.

Salvage TORS should only be undertaken by surgeons with extensive TORS experience, with preoperative planning for potential vascular control and reconstruction; a recent single-center series of 61 salvage cases reported no major perioperative complications, with 97% of patients tracheostomy-free and 93% gastrostomy-free at last follow-up [53]. The international RECUT cohort of 278 patients treated across 16 high-volume centers provides the most robust salvage evidence to date, reporting 2-year local control of 69.0% and overall survival of 71.8%, with hemorrhage requiring return to theater in 8.1% and 30-day mortality of 1.8% [54]. A French multicenter GETTEC series of 138 previously irradiated patients similarly confirmed feasible oncologic and functional outcomes, with morbidity concentrated in advanced recurrent disease [55], and a recent meta-analysis found that, relative to open salvage, transoral resection was associated with lower feeding-tube and tracheostomy dependence and higher 2-year overall survival in selected recurrent OPSCC [56].

Other reported complications include tooth injury in approximately 1.4% of cases related to mouth gag placement and instrument passage, transient hypoglossal nerve injury in approximately 0.9% typically resolving spontaneously, and lingual nerve injury in approximately 0.6% [48]. Surgical site infection after transoral resection is uncommon. Wound infection and pharyngocutaneous fistula are more common in salvage surgery and free flap reconstruction cases. Long-term gastrostomy tube dependence after primary TORS is uncommon; a large multi-institutional survey reported percutaneous gastrostomy dependence beyond six months in only about 1% of cases, with appreciably higher rates after salvage surgery [48,57]. Postoperative pain is generally manageable with multimodal analgesia; in a series of 216 patients, the use of scheduled ibuprofen was not associated with increased bleeding risk even in patients with severe pain, whereas scheduled low-dose gabapentin neither improved pain control nor reduced opioid requirements [58].

Despite the serious nature of these complications, perioperative mortality after TORS remains low. A National Cancer Database analysis of 4,127 patients reported 30- and 90-day mortality of 0.6% and 0.9%, respectively, with age 65 years or older being the principal predictor of perioperative death [59]. A separate Commission on Cancer analysis found 90-day mortality after TORS comparable to or lower than that after primary radiotherapy in appropriately selected patients [60]. Airway management practice, including the indications for preventive tracheostomy, nonetheless varies widely across centers, and a French GETTEC survey documented substantial heterogeneity that underscores the need for standardized protocols [61].

Level of evidence: Level 3–4 for most complication data; Level 4 for carotid injury and catastrophic hemorrhage due to rarity.

5. Clinical Application by Tumor Subsite

5.1. Oropharyngeal Cancer

Oropharyngeal squamous cell carcinoma, particularly HPV-associated disease, constitutes the most well-established and evidence-based indication for TORS. The majority of published TORS series focus on oropharyngeal primaries, reflecting the favorable anatomy of the tonsil and base of tongue for transoral robotic access [9,10].

For early-stage (T1–T2) OPSCC, TORS with or without neck dissection achieves high rates of local control (90–95%) and overall survival, with functional outcomes that compare favorably to historical open surgery controls [9,10]. Contemporary real-world comparisons of upfront TORS and IMRT in HPV-positive disease report comparable survival and increasingly inform a preference-based choice between the two modalities [30,32]. For more advanced (T3) lesions, TORS remains feasible in selected cases, but the likelihood of requiring adjuvant therapy increases substantially, and the functional benefit over primary (chemo)radiotherapy becomes less clear. Patient selection is paramount: tumors with extensive lingual artery involvement, deep tongue base infiltration, or mandibular invasion may not be suitable for TORS [62].

5.2. Laryngeal Cancer

TORS has been applied to selected laryngeal tumors, primarily supraglottic carcinomas. Robotic supraglottic laryngectomy offers the advantage of precise resection with wristed instruments in the confined laryngeal framework, with reported local control rates of 85–90% for appropriately selected T1–T2 supraglottic tumors [63,64]. A systematic review pooling 896 patients confirmed high local control together with low rates of permanent tracheostomy and gastrostomy after robotic supraglottic laryngectomy [65], and a comparative review reported onco-

logic outcomes comparable to open supraglottic laryngectomy with faster recovery of swallowing [66].

Glottic tumors are less commonly addressed via TORS due to limited access and the established role of transoral laser microsurgery and radiotherapy for early glottic disease. Selected supracricoid resections and partial laryngectomies have been described via TORS at specialized centers, but these remain investigational and require substantial expertise [67,68]. The role of TORS in laryngeal cancer is likely to remain focused on supraglottic and select transglottic tumors, with laser microsurgery and radiotherapy continuing to dominate glottic disease management.

5.3. Hypopharyngeal Cancer

Hypopharyngeal cancer represents a more challenging indication for TORS due to the anatomical proximity of the carotid sheath and the often-advanced stage at presentation. Selected early-stage hypopharyngeal tumors, particularly those arising in the pyriform sinus, may be amenable to TORS resection with appropriate exposure and careful vascular protection [7,69,70].

An NCDB analysis by Finegersh and colleagues suggested that TORS may be associated with improved overall survival for T1–T2 hypopharyngeal tumors compared to open surgery or primary radiotherapy [69]. A systematic review of TORS and endoscopic laryngopharyngeal surgery for hypopharyngeal cancer confirmed feasible organ-preserving resection with encouraging swallowing outcomes in selected patients [33,70], while a GETTEC multicenter study found comparable oncologic outcomes between transoral laser and robotic approaches to tongue base tumors [71]. However, these database and pooled findings are subject to selection bias, and prospective validation is lacking. TORS for hypopharyngeal cancer should be considered only at experienced centers, with careful preoperative imaging to exclude carotid invasion and with readiness for immediate conversion to open surgery if needed.

5.4. Nasopharyngeal and Parapharyngeal Space Tumors

TORS has been described for selected nasopharyngeal pathologies including recurrent nasopharyngeal carcinoma after radiotherapy and benign parapharyngeal space tumors [8,72]. The transoral approach provides direct access to the nasopharynx and parapharyngeal space without the need for external incisions or maxillary swing, potentially reducing surgical morbidity.

For recurrent nasopharyngeal carcinoma after definitive radiotherapy, TORS offers a salvage option for selected rT1–rT2 lesions. The largest robotic series, comprising 31 patients followed for a median of 38 months, reported a five-year local control rate of 85.1% in carefully selected tumors, although five-year overall survival remained limited (55.7%) owing to advanced recurrence and second events [73]; the earliest robotic report described a single favorably located case with minimal blood loss and smooth recovery, establishing technical feasibility rather than an oncologic benchmark [72]. Salvage surgery in the irradiated nasopharynx nonetheless carries elevated risks of bleeding, infection, and carotid exposure, and should only be undertaken at specialized centers. For benign parapharyngeal space tumors, contemporary surgical series show that transoral and other minimally invasive approaches can shorten hospital stay and reduce morbidity relative to transcervical or transparotid approaches in carefully selected, medially located lesions [8].

5.5. Cancer of Unknown Primary

TORS plays an established role in the diagnostic workup of cervical metastatic squamous cell carcinoma with unknown primary (CUP). Bilateral tonsillectomy and base-of-tongue resection via TORS identify the primary site in approximately 40–60% of cases, with higher detection rates when combined with directed biopsies of suspicious areas [74,75].

The diagnostic yield of TORS for CUP is superior to conventional blind biopsies or tonsillectomy alone, as the robotic system enables thorough inspection and targeted resection of the base of tongue, tonsils, and other oropharyngeal subsites under magnified 3D visualization. Recent meta-analyses and updated reviews confirm that transoral mucosectomy substantially increases primary-site detection compared with conventional workup [75,76], and a six-year single-center series reported minimal morbidity and durable diagnostic yield from robotic tongue base mucosectomy [77]. Identifying the primary site has important prognostic and therapeutic implications, potentially allowing for de-escalation of radiation fields and reduction of treatment-related toxicity. A cost-effectiveness analysis by Byrd and colleagues found TORS to be a cost-effective diagnostic strategy for CUP compared to traditional

workup approaches [78].

6. De-Escalation Therapy in HPV-Associated Oropharyngeal Cancer

The excellent prognosis of HPV-associated oropharyngeal cancer—with five-year overall survival rates of approximately 80–90% even for locally advanced disease—has generated intense interest in treatment de-escalation. The premise is straightforward: for patients whose tumors carry a favorable molecular profile, standard-intensity therapy may represent overtreatment, and reduction of radiation dose, chemotherapy, or both could substantially diminish long-term toxicity without compromising oncologic control [11,12].

6.1. Rationale and Risk Stratification Framework

De-escalation strategies employing TORS are predicated on postoperative pathologic risk stratification. Low-risk pathology—negative margins, no or minimal nodal disease, no extracapsular extension (ECE), no perineural or lymphovascular invasion—may permit observation alone or de-escalated adjuvant radiotherapy (e.g., 50 Gy without concurrent chemotherapy). Intermediate-risk features, such as close margins (<5 mm) or limited nodal disease without ECE, may warrant standard-dose radiotherapy (60 Gy) without concurrent chemotherapy. High-risk features—positive margins, ECE, multiple positive nodes—necessitate standard adjuvant chemoradiotherapy (60–70 Gy with concurrent cisplatin) [46,47].

The critical challenge is selecting patients preoperatively who are likely to fall into low- or intermediate-risk categories, thereby avoiding the scenario where surgery leads to the discovery of high-risk features that mandate full-intensity adjuvant therapy—a situation that effectively intensifies rather than de-escalates treatment. Clinical factors associated with low-risk pathology include T1–T2 primary tumors, clinically N0 or limited N1 nodal disease, and HPV/p16 positivity with low smoking history. Even with careful selection, however, a substantial proportion of surgically staged patients will harbor high-risk features requiring standard adjuvant CRT.

6.2. Key Clinical Trials

The ECOG-ACRIN 3311 trial is a phase II randomized study evaluating transoral surgery followed by risk-stratified adjuvant therapy for resectable p16-positive locally advanced oropharyngeal cancer [46]. Patients with low-risk pathology (negative margins, no more than one positive node, no ECE) were assigned to observation (arm A); patients with intermediate-risk pathology (negative margins, two to four positive nodes, or ECE ≤1 mm) were randomized to postoperative radiotherapy at 50 Gy (arm B) versus 60 Gy (arm C); and patients with high-risk features (positive margins, more than four positive nodes, or ECE >1 mm) received 60–66 Gy with concurrent weekly cisplatin (arm D).

At two years, progression-free survival (PFS) was excellent across all de-escalation arms: 96.9% for observation, 94.9% for 50 Gy, and 96.0% for 60 Gy [46]. These results support the safety of de-escalation in carefully selected low-risk patients, although longer follow-up is needed to confirm durability of oncologic control. The trial also demonstrated that a significant proportion of patients (approximately 30%) were upstaged to high-risk pathology requiring standard chemoradiotherapy, underscoring the challenge of patient selection.

The PATHOS trial (NCT02215265) is a UK-based phase II/III randomized controlled trial investigating de-escalation of adjuvant treatment after transoral surgery in HPV-positive oropharyngeal cancer [47]. The phase II portion established the safety of risk-stratified adjuvant therapy, and the phase III portion is currently comparing reduced-dose radiotherapy (50 Gy) versus standard-dose radiotherapy (60 Gy) in intermediate-risk patients, with quality of life and functional outcomes as primary endpoints.

As discussed in Section 4.3, the ORATOR trial compared primary TORS versus primary radiotherapy and found mixed functional results, with RT showing an early swallowing advantage [15]. ORATOR2, a phase II trial comparing de-escalated radiotherapy versus TORS with or without reduced-dose adjuvant RT, was terminated early due to unexpected treatment-related mortality in the surgery arm [16]. The phase II non-randomized Sinai Robotic Surgery (SIRS 2.0) trial is further evaluating risk-stratified de-intensified adjuvant therapy after TORS [79], while contemporary multidisciplinary consensus reviews emphasize that, until phase III data mature, de-intensification outside a clinical trial should remain confined to low-risk pathology [80]. These trials collectively underscore that TORS-based de-escalation is not without risk and that careful patient selection is essential.

6.3. Current Clinical Positioning

Despite promising early data, TORS-based de-escalation should currently be considered investigational and restricted to clinical trial settings or to highly selected patients within formal risk-stratified pathways at experienced centers. The available evidence comes primarily from phase II trials with relatively short follow-up, and phase III data confirming non-inferiority of de-escalated approaches are not yet mature.

Not all patients are de-escalation candidates. A substantial proportion of patients undergoing TORS will have high-risk pathologic features requiring standard adjuvant CRT, effectively intensifying rather than reducing treatment. The risk of triple-modality therapy—surgery plus radiotherapy plus chemotherapy—carries substantial acute and late toxicity and should be weighed carefully against primary (chemo)radiotherapy, which avoids surgical morbidity but entails radiation-specific late effects.

Ongoing phase III trials will better define the role of TORS in de-escalation strategies and identify which patient subgroups derive the greatest net benefit. Until these data mature, de-escalation decisions should be made within multidisciplinary tumor boards, with explicit discussion of the risks of both under-treatment and over-treatment, and with informed patient consent regarding the investigational nature of the approach.

7. Learning Curve and Training Requirements

Acquiring TORS proficiency represents a substantial training investment, and surgical outcomes are demonstrably linked to surgeon experience. Understanding the learning curve is essential for program implementation, credentialing, quality assurance, and patient counseling. Unlike many conventional surgical procedures, TORS introduces a novel human-machine interface that requires mastery of console operation, instrument articulation, and transoral exposure techniques that differ substantially from open surgery.

7.1. Quantification of the Learning Curve

Several studies have formally assessed the TORS learning curve using cumulative sum (CUSUM) analysis and other statistical methods, evaluating endpoints including operative time, margin status, complication rates, and conversion to open surgery. These analyses consistently demonstrate that the learning curve is real and measurable, with identifiable inflection points beyond which outcomes stabilize.

The most consistently demonstrated learning effect is in operative duration. A four-year analysis at the University of Alabama at Birmingham found that mean operative time decreased by 47% across four chronological groups, from 183 min in the earliest group to 86 min in the most experienced group, with total intubation time decreasing by 87% [22]. This reduction in operative time has practical implications for operating room efficiency, anesthesia duration, and cost.

Margin status represents a more clinically meaningful oncologic endpoint. In a CUSUM analysis of 382 identified TORS procedures, of which 160 performed by three surgeons met inclusion criteria, inflection points for positive margin status occurred at approximately 25–27 cases for two of three surgeons (with no inflection point for the third), while inflection points for time to resection ranged from 27 to 39 cases, demonstrating that the learning curve is surgeon-specific [23]. The authors emphasized that learning curves varied considerably among individual surgeons, with one surgeon showing no identifiable inflection point for margin status, underscoring that technical proficiency is achieved at different rates across operators.

Complication rates also improve with experience. The multi-institutional survey by Chia and colleagues found that complication rates decreased significantly after surgeons had performed more than 50 cases, with the most pronounced reduction observed in postoperative bleeding and airway complications [48]. This threshold of approximately 50 cases for complication reduction is higher than the 25–39 case inflection points reported for margin status and resection time, suggesting that managing complex intraoperative situations and avoiding complications requires greater cumulative experience than achieving basic procedural competence. **Table 2** summarizes the learning curve parameters for TORS in oropharyngeal cancer across these studies.

7.2. Factors Influencing Learning Curve Duration

Several factors modulate the steepness of the learning curve. Surgeons with established transoral endoscopic skills generally adapt more quickly to TORS [81]. This is particularly true for surgeons with experience in transoral

laser microsurgery, as the concepts of transoral exposure, tissue plane identification, and endoscopic depth perception are transferable. Case mix matters as well: oropharyngeal tonsil tumors, which are relatively accessible and have favorable anatomy, are generally easier initial cases than tongue base, supraglottic, or hypopharyngeal lesions, which require more advanced instrument manipulation and exposure techniques.

Table 2. Learning Curve Parameters for TORS in Oropharyngeal Cancer.

Study	Method	Endpoint	Inflection Point	Key Finding
White et al. (2013) [22]	Prospective, 4 chronological groups (42 each, 168 total)	Operative time, intubation time, LOS	Progressive improvement across groups	Operative time decreased 47% (183 to 86 min); intubation time decreased 87%
Albergotti et al. (2017) [23]	CUSUM, 382 procedures identified, 160 analyzed, 3 surgeons	Positive margin rate, time to resection	25–39 cases (surgeon-specific)	Surgeon-specific: margins at 25–27 cases (2 of 3 surgeons); resection time at 27–39 cases
Chia et al. (2013) [48]	Multi-institutional survey	Complications	>50 cases	Complication rates significantly decreased after >50 cases
Lawson et al. (2011) [81]	Retrospective, learning curve	Operative time	~20 cases	Learning curve primarily affects operative duration

Team familiarity is another important determinant. TORS is a team-based procedure requiring coordinated effort between the surgeon, bedside assistant, anesthesiologist, and operating room nursing staff. Teams that perform TORS regularly develop efficient workflows for patient positioning, oral cavity exposure, robot docking, and instrument exchange, which can substantially reduce setup time and improve overall procedural efficiency. Programs that perform fewer than 10–15 cases per year may struggle to maintain team proficiency and may experience longer operative times and higher complication rates.

7.3. Training and Credentialing

Current TORS training pathways typically include didactic coursework, simulation training, cadaveric laboratory sessions, observation of live cases, and proctored initial procedures under the supervision of an experienced TORS surgeon. The number of proctored cases required for independent practice varies by institution and jurisdiction, but ranges from 5 to 20 cases for basic oropharyngeal procedures, with additional cases required for more advanced applications such as laryngeal, hypopharyngeal, or salvage surgery.

Maintenance of proficiency also requires adequate case volume. The observed decline in complication rates with higher case volume suggests that periodic minimum caseload thresholds may be appropriate for quality assurance purposes. An international survey of otolaryngologist-head and neck surgeons documented wide geographic variation in TORS adoption, with access concentrated in high-volume North American and Asian centers and a persistent need for structured training pathways [82]. Institutions considering implementation of a TORS program should ensure sufficient patient volume to maintain surgeon and team proficiency, and should establish robust quality monitoring processes to track outcomes and identify areas for improvement.

Level of evidence: Level 3–4 for learning curve data, derived from retrospective single-institution series. No randomized comparisons of different training paradigms exist.

8. Health Economics and Cost-Effectiveness

The economic implications of TORS are substantial, given the high capital cost of robotic surgical systems, instrument costs, and the broader question of whether the perceived clinical benefits justify the additional expenditure. As healthcare systems worldwide face increasing cost constraints, understanding the cost-effectiveness of TORS relative to alternative treatments is essential for informed decision-making by policymakers, hospital administrators, and clinicians.

8.1. TORS versus Primary (Chemo)Radiotherapy

Multiple decision-analytic cost-effectiveness studies have compared TORS with primary radiotherapy or chemoradiotherapy for early-stage oropharyngeal cancer, with heterogeneous results. These studies employ different model structures, time horizons, cost assumptions, and effectiveness estimates, which partly explain the divergent conclusions.

A cost-utility analysis by de Almeida and colleagues using a Markov model with a 10-year horizon found that TORS was both less costly (savings of \$1,366 per patient) and more effective (gain of 0.25 quality-adjusted life years, QALYs) compared to (chemo)radiotherapy for early T-classification OPSCC [83]. The model was highly sensitive to the proportion of patients requiring adjuvant therapy, however: as adjuvant therapy rates increased, the cost-effectiveness advantage of TORS diminished and eventually reversed.

A real-world MarketScan database analysis of 3,573 surgically treated OPC patients found that TORS (n = 304, 8.5%), compared with non-robotic surgery, was associated with significantly lower overall treatment-related costs (mean incremental difference of -\$22,724), along with reduced one-year gastrostomy tube rates (OR 0.54) and tracheostomy rates (OR 0.17) [29]. Among patients receiving adjuvant radiation, concurrent chemotherapy was significantly less common in the TORS group (OR 0.52), suggesting that TORS may reduce the intensity of adjuvant therapy in real-world practice. Other studies have reached the opposite conclusion. A Markov analysis by Rudmik and colleagues comparing TORS versus IMRT for early-stage (T1–2N0) OPSCC over a five-year horizon found an incremental cost-effectiveness ratio (ICER) of \$165,300 per QALY for TORS, with only a 42% probability of TORS being cost-effective at a \$50,000/QALY willingness-to-pay threshold [84]. The authors concluded that IMRT was more likely to be cost-effective and advocated for consolidation of TORS into high-volume centers to improve efficiency.

For patients with clinical N2 HPV-positive OPSCC, Sher and colleagues found that primary CRT dominated TORS (7.31 QALYs at \$50,100 vs. 7.29 QALYs at \$62,200), with CRT remaining cost-effective under nearly all assumptions unless the locoregional recurrence risk after TORS was 30–50% lower [14]. This finding highlights that the cost-effectiveness of TORS is highly dependent on disease stage and the likelihood of requiring adjuvant therapy.

A microsimulation study by Rodin and colleagues for T1–2N0–1 OPSCC reported an ICER of \$82,190/QALY for TORS versus radiotherapy, with RT having a 54% probability of being more cost-effective [85]. The ICER was highly sensitive to the assumed rate of adjuvant therapy after TORS: when fewer than 30% of TORS patients required adjuvant CRT, TORS became cost-effective; when more than 50% required adjuvant CRT, RT dominated. **Table 3** summarizes the cost-effectiveness studies comparing TORS to primary radiotherapy/chemoradiotherapy.

Table 3. Summary of Cost-Effectiveness Studies Comparing TORS to Primary Radiotherapy/Chemoradiotherapy.

Study	Model Type	Population	ICER/Key Finding	Favors
de Almeida et al. (2016) [83]	Markov model, 10yr	Early T-stage OPSCC	TORS less costly (-\$1,366) and more effective (+0.25 QALY)	TORS
Motz et al. (2017) [29]	MarketScan real-world	Surgically treated OPC	TORS lower total costs (-\$22,724), lower G-tube (OR 0.54)	TORS
Rudmik et al. (2015) [84]	Markov model, 5yr	T1–2N0 OPSCC	ICER \$165,300/QALY for TORS vs. IMRT	RT
Sher et al. (2016) [14]	Decision analysis	Clinical N2 HPV+ OPSCC	CRT dominates TORS (7.31 QALYs/\$50,100 vs. 7.29 QALYs/\$62,200)	CRT
Rodin et al. (2017) [85]	Microsimulation	T1–2N0–1 OPSCC	ICER \$82,190/QALY; RT 54% probability more cost-effective	Mixed
Byrd et al. (2014) [78]	Cost-effectiveness	Unknown primary	TORS diagnostic approach cost-effective	TORS

8.2. Key Determinants of Cost-Effectiveness

Across studies, the most influential variables determining TORS cost-effectiveness are the rate of adjuvant therapy—consistently the strongest driver, with TORS cost-effective only when a substantial proportion of patients avoid or have reduced adjuvant therapy—and long-term toxicity costs, where TORS gains economic advantage over longer time horizons if it reduces late radiotherapy-related complications such as xerostomia, dysphagia, and dental costs. Quality-of-life utility assumptions also play a large role; small differences in assumed utility values between treatment arms can substantially alter ICERs. High-volume centers may achieve lower per-procedure costs and better outcomes, improving cost-effectiveness. Importantly, cost-effectiveness results are derived primarily from US healthcare pricing and may not generalize to single-payer or resource-limited systems.

8.3. Resource-Limited Healthcare Settings

In resource-constrained healthcare environments, the capital investment required for robotic surgical systems—including purchase price (typically \$1.5–2.5 million), annual service contracts, and disposable instrument costs—

constitutes a substantial barrier. In these settings, the cost-effectiveness of TORS is even more dependent on high procedural volume to amortize fixed costs, and on careful patient selection to ensure that the clinical benefits justify the expenditure. TORS may be most economically viable in large tertiary centers that can maintain sufficient case volume, serve as regional referral centers, and integrate TORS into broader head and neck cancer treatment pathways.

Level of evidence: Level 2–3 for cost-effectiveness data, all based on decision-analytic models with varying assumptions. No prospective trial-based economic evaluation exists.

9. Artificial Intelligence in TORS: Current Status and Future Directions

The integration of artificial intelligence with robotic surgery has generated considerable enthusiasm, with proposals spanning the entire perioperative pathway from preoperative planning to intraoperative guidance to postoperative outcome prediction. The actual evidence base for AI applications specifically validated within TORS workflows remains limited, however. This section critically appraises the current state of AI applications relevant to TORS, explicitly distinguishing between TORS-specific clinical validation, general head and neck cancer evidence, and preclinical or extrapolated data.

9.1. Preoperative Tumor Segmentation and Treatment Planning

Accurate delineation of primary tumor and nodal volumes is essential for surgical planning, margin estimation, and radiotherapy planning. Deep learning-based automated segmentation has been extensively studied in head and neck cancer, primarily in the context of radiotherapy planning.

The HECKTOR (Head and Neck Tumor Segmentation) challenge, a multi-institutional benchmark for automated gross tumor volume (GTV) segmentation on FDG-PET/CT images of oropharyngeal cancer, has demonstrated that state-of-the-art deep learning models achieve mean Dice similarity coefficients (DSC) of 0.75–0.80 on independent test sets [86]. Kovacs and colleagues conducted a clinical evaluation of deep learning for tumor delineation on 18F-FDG PET/CT of head and neck cancer, finding that AI-assisted segmentation substantially reduced delineation time while maintaining accuracy comparable to expert manual segmentation [87]. Wang and colleagues compared multiple deep learning networks for fully automated head and neck tumor delineation on multi-centric PET/CT images, finding that nnU-Net achieved the best performance (DSC 0.81), suggesting generalizability of these models across institutions [88].

For MRI-based segmentation, Schouten and colleagues used a multi-view CNN for automatic segmentation of head and neck primary tumors on MRI, demonstrating feasibility of MRI-based segmentation [89]. De Biase and colleagues developed a deep learning method using adaptive thresholding of predicted tumor probability in FDG PET and CT images, generating probability maps that capture model uncertainty in segmentation and providing radiation oncologists with slice-by-slice adaptive GTV segmentation guidance [90].

While these segmentation results are encouraging, several important caveats apply to TORS specifically. All published AI segmentation studies for head and neck tumors have been developed and validated for radiotherapy planning rather than surgical resection planning. The requirements for surgical segmentation differ from radiotherapy planning: surgery demands more precise delineation of mucosal margins, estimation of deep margins, and relationship to critical vascular and neural structures, whereas radiotherapy segmentation typically includes larger clinical target volume (CTV) margins. Furthermore, these models have been trained and validated on pretreatment images without accounting for intraoperative tissue deformation, which is a significant challenge in TORS.

Evidence level for TORS application: Preclinical/extrapolated. No study has prospectively validated AI tumor segmentation within an actual TORS workflow or demonstrated improvement in surgical margins, operative time, or oncologic outcomes.

9.2. Intraoperative Navigation and Augmented Reality

Augmented reality (AR) navigation—whereby preoperative or intraoperative imaging is overlaid onto the surgeon's endoscopic view—has been proposed as a means to improve tumor localization, margin adequacy, and avoidance of critical vascular structures during TORS.

The most developed AR system for TORS comes from the Johns Hopkins group, who have investigated cone-

beam CT (CBCT)-based image guidance integrated with the da Vinci system. In preclinical studies using porcine tongue and cadaveric head models, Liu and colleagues demonstrated that intraoperative CBCT guidance, overlaid via video enhancement on the main stereoscopic endoscopic view, improved target localization accuracy and reduced resection time compared to control and alternative navigation methods [91,92]. The system uses a surgical plan defined on preoperative CT/MRI, which is then registered to the actual surgical anatomy via intraoperative CBCT, with tumor boundaries and critical structures superimposed on the endoscopic view.

A broader review of imaging-based navigation technologies in head and neck surgery by Eu and colleagues summarizes the expanding landscape including CT/MRI/PET fusion, intraoperative CBCT, VR/AR integration, and fluorescence imaging, but notes that most applications remain at early stages of development with limited clinical translation [93]. The review emphasizes that soft tissue deformation—a particular challenge in the head and neck region—remains a major limitation to image-guided navigation accuracy, necessitating deformable registration algorithms and intraoperative imaging modalities to address.

All AR-TORS studies to date have been conducted in phantom, animal, or cadaveric models. No clinical trial or clinical case series has been published demonstrating AR navigation in actual human TORS procedures. The significant soft tissue deformation between preoperative imaging and intraoperative anatomy—due to oral cavity exposure, instrument manipulation, and tissue retraction—remains a major technical barrier to clinical translation. Furthermore, the registration accuracy of AR overlays with actual anatomy has not been adequately validated in the clinical setting.

Evidence level for TORS application: Preclinical (animal/cadaver). Promising proof-of-concept data exist, but clinical translation and validation in human TORS are pending.

9.3. Intraoperative Margin Assessment

Intraoperative assessment of surgical margins is critical in TORS, as positive or close margins may necessitate additional resection or escalation of adjuvant therapy. Several AI-enhanced optical imaging modalities have been investigated for real-time margin assessment in head and neck cancer.

Fluorescence lifetime imaging microscopy leverages differences in the autofluorescence decay profiles of normal and malignant tissues to distinguish tumor from healthy mucosa. Marsden and colleagues developed a data-centric AI approach for label-free FLIm-based intraoperative tumor margin delineation in oral and oropharyngeal cancer patients [94]. The system uses a random forest classifier to analyze FLIm data, generating cancer probability maps that can be overlaid on the surgical view to guide resection. Bali and colleagues developed a hyperspectral imaging (HSI) system combining deep learning and three-dimensional tumor modeling for real-time intraoperative decision-making in head and neck tumor surgery, demonstrating feasibility in freshly resected HNSCC specimens [95].

While these optical imaging approaches are conceptually compatible with robotic platforms and could theoretically be integrated with the da Vinci endoscope, none have been specifically validated within TORS procedures. Most studies use benchtop imaging systems or handheld probes, and integration with robotic surgical systems would require additional engineering development and validation. Furthermore, the performance of these systems in the in vivo TORS environment—where motion artifacts, blood, and tissue deformation may affect image quality—has not been evaluated.

Evidence level for TORS application: Extrapolated from general head and neck cancer studies. No TORS-specific intraoperative margin AI system has been clinically validated.

9.4. Postoperative Complication and Outcome Prediction

Machine learning models have been developed to predict postoperative complications in head and neck surgery, which could potentially inform preoperative counseling, risk stratification, and resource allocation.

Tighe and colleagues applied machine learning algorithms to a dataset of 1,254 head and neck cancer surgery patients and developed models predicting any 30-day complication (AUROC 0.72), severe complications (AUROC 0.70), and prolonged hospital stay >15 days (AUROC 0.81) [96]. Deep learning has also been applied to pathologic risk stratification: using baseline CT images from the multicenter ECOG-ACRIN 3311 de-escalation trial, a CT-based deep learning algorithm screened for extranodal extension in HPV-associated oropharyngeal carcinoma with high concordance with central pathology review, illustrating the potential of AI to refine preoperative risk selection [97].

Santoro and colleagues developed an algorithm to predict postoperative complications in oropharyngeal and oral cavity carcinoma patients, suggesting these models can identify high-risk patients for close monitoring and early intervention [98]. Koenen and colleagues developed machine learning models to predict surgical complications after laryngectomy, demonstrating feasibility of these approaches in specific surgical populations [99]. Formeister and colleagues developed machine learning models for predicting complications in head and neck microvascular free tissue transfer, demonstrating feasibility in reconstructive surgery as well [100].

None of these models were developed specifically for TORS patient populations. TORS has a distinct complication profile—dominated by postoperative hemorrhage rather than surgical site infection or flap complications—and differs from open head and neck surgery or chemoradiotherapy in patient demographics. Extrapolating models developed for broader head and neck surgery populations to TORS patients requires careful validation and calibration, as predictors of complications and baseline risks may differ.

Costantino and colleagues have developed machine learning models specifically for predicting positive surgical margins in TORS, representing one of the few TORS-specific AI applications in the literature [101]. The model uses preoperative clinical and imaging features to predict risk of positive margins, potentially aiding patient selection and surgical planning. However, the model was developed and validated in a single-institution retrospective cohort and requires external validation in independent cohorts.

Evidence level for TORS application: Mostly extrapolated. One TORS-specific margin prediction model exists (Level 3 evidence); complication prediction models are from broader head and neck surgery populations.

9.5. Surgical Skill Assessment and Training

AI-based automated evaluation of surgical performance has been proposed as a tool for TORS training, credentialing, and quality assurance. Automated surgical skill assessment using machine learning analysis of surgical video or kinematic data has been extensively studied in laparoscopic and general robotic surgery. Systematic reviews have documented a growing literature on AI-derived performance assessment in both surgical simulation and actual procedures, with reported skill classification accuracies ranging from 75–90% depending on the task and assessment metrics [102,103]. These systems employ various approaches including convolutional neural networks for video analysis, hidden Markov models for kinematic analysis, and multimodal methods combining video and kinematic data.

While the da Vinci system generates rich kinematic and video data that could theoretically support automated skill assessment, no published studies have validated AI-based skill evaluation specifically within TORS procedures. The anatomical complexity and unique instrument dynamics of transoral robotic surgery—substantially different from laparoscopic or abdominal robotic surgery—mean that skill assessment models developed for other surgical specialties may not directly generalize to TORS. Furthermore, the definition and assessment criteria for proficient performance in TORS remain evolving and require expert consensus and validation.

Evidence level for TORS application: Extrapolated from other surgical specialties. No TORS-specific surgical skill AI assessment system has been validated.

9.6. Limitations and Implementation Barriers

The translation of AI technologies into routine TORS practice faces substantial technical, clinical, regulatory, and ethical barriers. Technical barriers include dataset bias and generalizability—most AI models are trained on single-institution datasets with limited demographic and pathological diversity, and performance on external datasets from different institutions, scanners, and patient populations frequently degrades significantly. The considerable inter-patient variability in head and neck anatomy—including tonsillar size, tongue base morphology, and vascular anatomical variants—poses additional challenges to model generalization. Furthermore, most models have been trained and validated on static preoperative images without accounting for intraoperative tissue deformation and dynamic changes, which represent a significant challenge in TORS.

Clinical validation gaps remain significant. Virtually all AI applications relevant to TORS remain at the retrospective or preclinical stage. No randomized trial has demonstrated that any AI tool improves clinically relevant endpoints—margin status, complication rates, functional outcomes, survival, or quality of life—in TORS patients. Most studies use surrogate endpoints such as segmentation accuracy (DSC), classification accuracy, or prediction model AUROC, whose relationship to patient outcomes has not been established. Prospective clinical trials will be

essential to demonstrate the clinical utility and cost-effectiveness of AI tools within actual TORS workflows.

Regulatory and medico-legal barriers include evolving regulatory frameworks for AI surgical tools, with clearance pathways for intraoperative AI decision-support systems not yet well established in most jurisdictions. Liability and accountability when AI-assisted decisions lead to adverse outcomes remain unresolved—should the surgeon, hospital, AI developer, or regulatory agency bear responsibility? Furthermore, the continuous learning and updating of AI systems—which may change performance over time—pose challenges for regulatory approval and post-market surveillance.

Human factors introduce additional challenges. Automation bias—over-reliance on AI recommendations leading to complacency and errors, particularly when AI outputs are incorrect but appear confident—is a recognized risk. AI tools that do not integrate seamlessly with existing surgical workflows—for example, requiring the surgeon to leave the console to view a separate display—may increase cognitive load and disrupt surgical flow rather than improving it. The interpretability and transparency of AI outputs—particularly for deep learning models, which are often ‘black boxes’—are critical for surgeon trust and appropriate use of these tools.

Equity considerations compound these concerns. The integration of AI with robotic surgery risks exacerbating existing healthcare disparities. The high capital costs of both robotic platforms and AI systems concentrate capability at large academic centers, potentially widening the gap between high-volume and low-volume centers and between urban and rural areas. Furthermore, AI models trained on datasets derived predominantly from specific populations (often white, male, high-income) may perform poorly in other populations, leading to systematic bias in diagnostic and treatment recommendations. Deliberate efforts will be needed to ensure that the development and deployment of AI technologies promote health equity rather than exacerbating disparities.

Overall assessment of AI in TORS: The field is at an early, predominantly preclinical stage. While several technology streams show theoretical promise, the gap between demonstrated technical performance on surrogate endpoints and validated clinical benefit in actual TORS procedures remains substantial. Rigorous prospective clinical trials, multi-institutional external validation, and careful assessment of implementation barriers will be essential before AI can be considered an established component of TORS practice. **Table 4** provides a systematic evidence level assessment of the AI applications relevant to TORS discussed in this section.

Table 4. Evidence Level Assessment of AI Applications Relevant to TORS.

AI Application	Current Stage	TORS-Specific Validation	Best Evidence Level	Key Limitation
Tumor segmentation (PET/CT, MRI)	Retrospective, developed for RT planning	None	Preclinical/extrapolated	No surgical validation; developed for RT not surgery
AR navigation (CBCT-based)	Preclinical (animal/cadaver)	Johns Hopkins preclinical studies	Preclinical (Level 5)	No human clinical TORS data; soft tissue deformation
Intraoperative margin assessment (FLIm, HSI)	General H&N cancer studies	None	Extrapolated (Level 3–4)	No TORS-specific validation; motion artifacts in vivo
Complication/outcome prediction	General H&N surgery models	One TORS-specific margin model	Mostly extrapolated (Level 3)	TORS has distinct complication profile (bleeding)
Surgical skill assessment	Laparoscopic/general robotic	None	Extrapolated from other specialties	TORS anatomy and instrument dynamics differ
Overall AI integration in TORS	Early, predominantly preclinical	Very limited	Level 4–5	Substantial gap between technical performance and clinical benefit

10. Future Directions

Several evolving directions are likely to shape the role of TORS in head and neck oncology over the coming decade. Next-generation robotic systems promise to address current limitations of TORS. The single-port (SP) platform may reduce instrument clashing and improve access to narrower anatomical spaces, and early clinical experience with transoral tonsillectomy and oropharyngeal resection has demonstrated feasible docking and adequate exposure, first in a prospective one-year single-port series and subsequently in case reports [104,105]. Advances in haptic feedback—currently absent in the da Vinci system—may enhance tactile assessment of tissue consistency and vascular structures, potentially reducing intraoperative complications. Smaller, more flexible instruments and improved ergonomic design may further expand the anatomical reach of TORS. Furthermore, native integration with intraoperative imaging modalities such as CBCT, optical coherence tomography, and fluorescence imaging may enable real-time image guidance without the complex registration and overlay required by current systems.

As surgeon experience accumulates and long-term outcome data mature, TORS indications may expand into currently more controversial areas. Carefully selected T3 and even T4a lesions in experienced hands, with appropriate reconstruction, represent a frontier. Salvage TORS for recurrent disease after radiotherapy may see expanded indications as experience grows, although careful patient selection and adequate reconstructive preparation remain essential. Additionally, TORS applications in non-malignant conditions such as base-of-tongue reduction for obstructive sleep apnea and tonsillectomy for chronic tonsillitis may increase, although the evidence base for these indications remains evolving.

Ongoing and planned phase III de-escalation trials—including the phase III portion of PATHOS and other international collaborative efforts—will more definitively establish the role of TORS within risk-adapted treatment algorithms for HPV-associated OPSCC. Results will inform guidelines regarding which patient subgroups derive the greatest net benefit from TORS-based de-escalation, which patients should receive primary (chemo)radiotherapy, and the optimal intensity of adjuvant therapy. Furthermore, trials comparing TORS with transoral laser microsurgery and other minimally invasive approaches will help define the best indications for each modality.

The integration of intraoperative imaging—CBCT, optical coherence tomography, fluorescence imaging, and eventually AR navigation—into routine TORS practice has the potential to improve margin accuracy and reduce the risk of vascular injury. However, as discussed in Section 9, clinical translation will require addressing challenges of soft tissue deformation, registration accuracy, and integration with robotic platforms. Hybrid operating rooms—combining robotic surgery, intraoperative imaging, and real-time pathology assessment—may become the standard for complex head and neck cancer surgery, enabling multidisciplinary teams to perform resection, immediate reconstruction, and adjuvant treatment planning in a single surgical episode.

Looking further ahead, AI has the potential to impact multiple stages of the TORS pathway: preoperative risk stratification and patient selection, intraoperative navigation and margin guidance, real-time complication prediction, and postoperative outcome monitoring. Realization of this potential will require rigorous prospective validation, addressing technical and regulatory barriers, and demonstrating improvement in patient outcomes rather than merely technical performance metrics. The integration of AI with robotic surgery is likely to evolve gradually, beginning with adjunctive tools and progressing toward more autonomous systems as the evidence base matures. It is important to emphasize that AI should augment rather than replace surgical judgment, and that the human surgeon will always bear ultimate responsibility for surgical decisions and patient outcomes.

As healthcare systems increasingly emphasize value-based care, formal health technology assessments of TORS will become more important. Comparative effectiveness research incorporating both clinical outcomes and cost data will be needed to guide resource allocation, particularly in publicly funded healthcare systems. Furthermore, real-world evidence studies will be essential to evaluate the effectiveness and cost-effectiveness of TORS in routine clinical practice, complementing the efficacy data from clinical trials. Routine collection of patient-reported outcome measures (PROMs) will enable healthcare systems to assess the impact of TORS on quality of life and inform quality improvement and reimbursement decisions.

11. Conclusion

Transoral robotic surgery has established itself as a valuable modality in the surgical armamentarium for head and neck cancer, particularly for early-stage oropharyngeal disease. When applied to appropriately selected patients by experienced surgeons, TORS achieves high rates of oncologic control, acceptable functional outcomes, and a favorable safety profile. TORS plays important roles in the diagnostic workup of cervical metastasis of unknown primary, in selected laryngeal and hypopharyngeal tumors, and within risk-adapted de-escalation strategies for HPV-associated oropharyngeal cancer.

Several important caveats temper enthusiasm, however. High-level randomized evidence comparing TORS to alternative treatments remains limited and yields nuanced results. The ORATOR trial challenges the assumption of universal functional superiority, demonstrating that primary radiotherapy may yield superior early swallowing-related quality of life compared to TORS, although long-term outcomes are similar. TORS and radiotherapy have distinct toxicity profiles, and the definition of ‘better’ functional outcomes depends on which specific domains and time points the patient prioritizes.

The role of TORS in treatment de-escalation for HPV-associated oropharyngeal cancer is promising but remains investigational. Trials such as ECOG-ACRIN 3311 and PATHOS provide encouraging early data supporting

risk-adapted de-escalation, but the risk of pathologic upstaging leading to triple-modality therapy is a significant concern that necessitates careful patient selection. Until phase III trial data mature, TORS-based de-escalation should be restricted to clinical trial settings or highly selected patients.

Cost-effectiveness analyses yield divergent conclusions depending on model assumptions, particularly the rate of adjuvant therapy required. TORS appears economically favorable primarily when it reduces the need for adjuvant therapy; for patients with advanced nodal disease who are likely to require standard adjuvant chemoradiotherapy, primary (chemo)radiotherapy is generally more cost-effective. High capital costs in resource-limited healthcare settings represent an additional economic barrier.

Artificial intelligence applications relevant to TORS—including automated segmentation, AR navigation, fluorescence margin assessment, and outcome prediction—remain largely at preclinical or early developmental stages. Most existing evidence derives from general head and neck imaging studies or other surgical specialties rather than from TORS-specific validation. Although proof-of-concept results are encouraging, no AI application has yet improved clinically relevant outcomes within a TORS workflow, and current evidence rests largely on surrogate end-points rather than patient-centered measures. Routine clinical application will therefore require rigorous prospective validation and demonstration of improved patient outcomes.

Looking forward, ongoing randomized trials, continued technological refinement of robotic platforms, gradual maturation of AI applications with rigorous clinical validation, and growing real-world outcome data will collectively define the optimal role of TORS within the multidisciplinary management of head and neck cancer. TORS is not a one-size-fits-all solution for all patients, but rather a precision tool that requires careful patient selection, appropriate training, and multidisciplinary collaboration. When applied in this manner, TORS can offer significant clinical benefits to selected head and neck cancer patients while minimizing treatment-related morbidity.

Author Contributions

Conceptualization, Q.H. and L.T.; literature review, Q.H., C.H., J.Z., and C.X.; drafting, Q.H. and C.H.; critical revision, J.Z., C.X., and L.T.; supervision, L.T. All authors read and approved the final manuscript.

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AI Use Statement

During the preparation of this manuscript, the authors used ChatGPT solely for language refinement. No AI tools were used for data analysis, interpretation, or generation of scientific content. All outputs were critically reviewed and edited by the authors. The authors take full responsibility for the integrity and accuracy of the work.

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