Literature Review

The influence of AI-driven robotics on medical education in head and neck surgery

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ABSTRACT

Background: Robotic surgery has become increasingly relevant in head and neck procedures, offering enhanced precision, improved access to anatomically complex regions, and favorable functional and cosmetic outcomes. Technological advances, including the integration of artificial intelligence (AI) and the emergence of novel platforms, have expanded the scope of minimally invasive surgery in Otolaryngology. However, disparities in access, training, and evidence quality, remain barriers to widespread adoption. **Purpose:** To evaluate the current impact of robotic surgery in head and neck surgery by synthesizing recent evidence on its clinical applications, technological development, training infrastructure, and future directions. **Method:** A narrative literature review was conducted using PubMed, Scopus, and Web of Science databases to identify peer-reviewed articles published between January 2010 and February 2025. Ten studies were selected based on relevance to robotic surgery in head and neck procedures. Data were extracted regarding study design, participants, intervention, outcomes, and thematic contributions. **Result:** The reviewed studies consistently demonstrated that robotic surgery was feasible and safe for transoral procedures, neck dissections, and pediatric cases. New platforms like Versius and KD-SR-01 showed potential for improved accessibility and usability. Key barriers included high cost, limited training availability, and lack of randomized controlled trials. AI applications remain largely theoretical with minimal clinical integration. **Conclusion:** Robotic surgery in head and neck practice is advancing with strong clinical promise. Future efforts must focus on cost-effectiveness, standardized training, and translational research to optimize access and impact, especially in under-resourced settings.

Keywords: artificial intelligence, robotic surgery, medical education, otolaryngology training, surgical simulation

ABSTRAK

Latar belakang: *Bedah robotik semakin berkembang dalam prosedur tindakan kepala dan leher, menawarkan presisi yang lebih tinggi, memudahkan akses ke area anatomi yang kompleks, serta hasil fungsional dan estetika yang lebih baik. Kemajuan teknologi, termasuk integrasi kecerdasan buatan* (AI) *dan munculnya* platform *robotik baru, telah memperluas cakupan bedah invasif minimal di bidang Otolaringologi. Namun, ketimpangan dalam akses, pelatihan, dan kualitas pembuktian, masih menjadi hambatan dalam adopsi luas teknologi ini.* ***Tujuan:*** *Mengevaluasi dampak terkini dari bedah robotik dalam bidang kepala dan leher melalui sintesis literatur yang membahas aplikasi klinis, perkembangan teknologi, infrastruktur pelatihan, dan arah masa depan.* ***Metode:*** *Tinjauan literatur naratif dilakukan dengan mencari artikel ilmiah di* database PubMed, Scopus, *dan* Web of Science *yang diterbitkan antara Januari 2010 hingga Februari 2025. Sepuluh studi dipilih berdasarkan relevansinya dengan bedah robotik pada prosedur kepala dan leher. Data diekstraksi berdasarkan desain studi, partisipan, intervensi, hasil, dan kontribusi tematik.* ***Hasil:*** *Menunjukkan bahwa bedah robotik aman dan layak dilakukan pada prosedur transoral, diseksi leher, dan kasus pediatrik.* Platform *baru seperti* Versius *dan* KD-SR-01 *menunjukkan potensi untuk meningkatkan keterjangkauan dan kemudahan penggunaan.*

Hambatan utama termasuk biaya tinggi, keterbatasan pelatihan, dan kurangnya uji coba acak. Aplikasi AI *masih bersifat teoritis dan belum banyak digunakan secara klinis.* ***Kesimpulan:*** *Bedah robotik dalam bidang kepala dan leher menunjukkan prospek klinis yang kuat. Upaya ke depan harus difokuskan pada efektivitas biaya, pelatihan terstandarisasi, dan penelitian kualitatif untuk memperluas akses dan dampaknya, terutama di daerah dengan sumber daya terbatas.*

Kata kunci: *kecerdasan buatan, bedah robotik, pendidikan medis, pelatihan otolaringologi, simulasi bedah*

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INTRODUCTION

The development of robotic and endoscopic minimally invasive technologies has facilitated a transition from open surgery to minimally invasive head and neck surgery in the past two decades.[1,2] Robotic surgery represents a transformative advancement in modern surgical practice, enabling minimally invasive procedures with greater precision, reduced trauma, and improved functional outcomes. In the context of head and neck surgery, a field characterized by complex anatomical structures, limited surgical access, and the need to preserve vital functions such as speech, swallowing, and aesthetics robotic systems have emerged as promising tools to overcome long-standing technical limitations. The refinement of robotic platforms has facilitated novel surgical approaches, particularly in regions that are traditionally difficult to reach through conventional open or endoscopic techniques.[3-6]

The origin of the term "robot" can be traced back to the Czech playwright Karel Čapek, who introduced the word in his 1920 theatrical work *Rossum's Universal Robots*, derived from the Czech word *rabota*, meaning forced labor. Although the concept of robotics emerged early in the twentieth century, substantial progress in robotics and computer technology accelerated several decades later, particularly with the incorporation of robotic systems into industrial manufacturing during the 1960s. The adoption of robotics in medicine developed more gradually. One of the earliest applications of robotic technology in surgery was reported by Yik San Kwoh et al.[7] in 1988, who utilized a modified industrial robotic arm known as the Puma 560 to perform highly precise neurosurgical biopsies.

Subsequent advancements resulted from collaborative efforts involving organizations such as the National Aeronautics and Space Administration (NASA), the SRI International, and the United States Department of Defense. Continued technological innovation throughout the 1990s ultimately contributed to the establishment of Intuitive Surgical in 1995, which integrated multiple prototype concepts and engineering developments to create some of the first surgical robotic systems used in human procedures during the late 1990s.[7,8]

The integration of robotic surgery in head and neck procedures began with the adaptation of the Da Vinci Surgical System, which offered enhanced dexterity, three-dimensional visualization, and tremor reduction capabilities. These features have been particularly valuable in transoral robotic surgery (TORS), where access to the oropharynx, larynx, and base of tongue is often restricted by conventional instrumentation.[5,9] TORS has since become an established approach for managing oropharyngeal malignancies and sleep apnea, demonstrating favorable oncologic control and functional outcomes with minimal invasiveness.[5,8,9] As surgical interest grows, additional platforms such as the Versius robotic system and the KD-SR-01 are being developed and tested, expanding the range of available tools for head and neck surgeons. These newer systems are designed to reduce costs and improve accessibility, particularly in regions where traditional robotic platforms are financially prohibitive.[4,10,11]

Despite these advancements, the field continues to face significant challenges. The high cost of robotic equipment, maintenance, and consumables remains a critical barrier to widespread adoption. Moreover, the limited availability of robotic systems in low- and middle-income settings has created disparities in access to advanced surgical care. Training requirements, steep learning curves, and the lack of standardized curricula further complicate the integration of robotic surgery into routine clinical practice.[9,12] While the emergence of artificial intelligence (AI) in surgical planning and decision-making holds future promise, its practical applications in robotic-assisted head and neck procedures are still in early experimental stages.[3,13]

There is also a pressing need for more robust clinical data. Most available studies are limited by small sample sizes, short follow-up durations, and heterogeneity in surgical techniques and patient populations. Long-term oncologic outcomes, functional recovery metrics, and cost-effectiveness analyses remain underreported. In pediatric and craniofacial surgery, robotic systems show potential in reducing iatrogenic injury and improving precision, but published evidence is scarce and largely anecdotal.[12]

Given these opportunities and ongoing challenges, the continued evaluation of robotic systems in head and neck surgery is of considerable importance. As healthcare systems seek to balance innovation with cost-effectiveness and equitable access, a clear understanding of the current evidence is essential to inform practice and policy.[5,6]

This review aimed to synthesize current literature on the application and impact of robotic surgery in head and neck procedures, evaluating clinical outcomes, technological advancements, and existing barriers, while identifying future directions for research and clinical practice.

METHOD

This article presented a narrative literature review aimed at synthesizing the current state of knowledge on the application and impact of robotic surgery in head and neck procedures. The review focused on clinical outcomes, technological advancements, training considerations, and emerging challenges associated with robotic systems in this specialized field.

A comprehensive search was conducted across three major scientific databases: PubMed, Scopus, and Web of Science. The search included articles published from January 2010 to February 2025, with the aim of capturing the most relevant and up-to-date developments in robotic-assisted head and neck surgery. The keywords were used in various combinations: “robotic surgery”, “robot-assisted”, “head and neck surgery”, “transoral robotic surgery”, “otolaryngology”, “AI in surgery”, and “robotic platforms”. Filters were applied to include only studies published in English.

The inclusion criteria were as follows: original research articles, clinical trials, case series, preclinical studies, and systematic or narrative reviews focused on robotic applications in head and neck surgery. Studies that addressed technical, clinical, training, or cost-related aspects of robotic platforms such as the Da Vinci Surgical System, Versius

System, and KD-SR-01. Articles discussing future perspectives or the integration of artificial intelligence in robotic systems within the surgical context.

Exclusion criteria included: Non-peer reviewed sources such as conference abstracts, letters to the editor, and editorial commentaries. Articles that did not specifically address head and neck applications of robotic surgery. Studies exclusively focused on robotic surgery in unrelated surgical fields (e.g., cardiac, urologic, or gynecologic procedures) unless they provided relevant comparative insights.

All retrieved articles were screened by title and abstract. Full-text reviews were performed for those meeting the inclusion criteria. The data were manually extracted and analyzed by the authors. Thematic grouping was applied to synthesize findings under key domains: (1) clinical applications and outcomes, (2) robotic system development and comparative performance, (3) training and accessibility, and (4) future directions including AI integration.

Although this was a narrative review and not a systematic review or meta-analysis, careful attention was given to selecting high-quality studies indexed in reputable databases. When available, studies with Level I–III evidence were prioritized. Preclinical trials were also included when they demonstrated novel or emerging technologies relevant to future clinical translation.

RESULT

The review of ten recent studies on robotic surgery in head and neck procedures revealed a growing consensus around the feasibility, safety, and evolving potential of robotic platforms in clinical and training contexts. Established systems like the Da Vinci Surgical System and emerging platforms such as Versius and KD-SR-01 showed encouraging results in improving surgical access, reducing cognitive workload, and enhancing patient outcomes, particularly in transoral and neck dissection procedures.[4,5,12,14] Case-based and preclinical evidence supports the safe translation of robotic-assisted training into clinical performance, as demonstrated in mannequin-based simulation followed by successful live surgery.[4]

Artificial Intelligence (AI) is also increasingly positioned as a transformative adjunct in robotic surgery, offering expanded planning and prognostic capabilities.[3,9] However, its integration into operative workflows and surgical education remains largely conceptual, with no empirical data validating its use intraoperatively. Across the reviewed literature, simulation-based learning and hybrid access techniques (e.g., robotic-endonasal combinations) suggest that future training models will require adaptation to accommodate technological complexity and procedural innovation.[4,15]

Despite this progress, notable gaps persist. Most studies lacked formal evaluation of educational outcomes, structured curricula, or long-term impacts on surgical skill development.[6,10] Institutional and geographic disparities in training access remain prominent, particularly among younger surgeons who express enthusiasm for robotic surgery but report limited opportunities due to cost and infrastructure.[6] Cost continues to be the most debated issue—whether the clinical and cosmetic benefits of robotic systems justify the financial investment is still unresolved.[12,13] Moreover, ethical concerns persist around pediatric and autonomous applications, where clinical risk, educational appropriateness, and regulatory readiness must be carefully addressed.[3,10] Robotic surgery is poised to become a mainstay in head and neck procedures, but its full educational and systemic integration demands further research, policy refinement, and equity-focused planning.[6]

Table 1. Summary of studies on robotic surgery and AI integration in head and neck surgery

Author	Design	Participants / model	Intervention / focus	Main finding	Limitation
Sriram et al., 2024	Narrative review	Not applicable	AI and semiautonomous robotics in ENT surgery	AI may improve surgical planning and automation in head and neck surgery	No clinical validation or patient outcome data
Agne et al., 2025	Preclinical study + human case	Simulation model and 1 patient	Versius system for TORS	Demonstrated feasibility and successful clinical translation after simulation training	Very limited sample size
Ma Z. et al., 2024	Expert review	Not applicable	Challenges in robotic head and neck surgery	Identified barriers including cost, training, and accessibility	Lack of empirical clinical data
Ma Z. et al., 2024	Preclinical animal study	Porcine models	KD-SR-01 robotic platform	Reduced cognitive workload and effective surgical performance	No human clinical application
Wojtera et al., 2024	Narrative review	Not applicable	AI applications in head and neck surgery	AI has potential in diagnosis, planning, and prognosis prediction	Mainly theoretical discussion
Whiteman et al., 2025	Narrative review	79 pediatric cases from literature	Robotic systems in pediatric craniofacial surgery	High success rate and low complication profile	Limited high-quality pediatric evidence
Dabas et al., 2024	Prospective observational study	82 patients	Robotic neck dissection via modified BABA technique	Favorable oncologic and cosmetic outcomes	No randomized comparison
Lechien et al., 2024	Cross-sectional survey	120 young ENT surgeons	Perception toward TORS	Surgeons showed interest but reported limited access and training	Opinion-based data without clinical outcomes
Sommerfeldt et al., 2024	Retrospective case series	35 patients	Da Vinci Xi system for TORS	Feasible and safe even in low-volume centers	Small sample and no control group
Wagner et al., 2025	Case report	1 patient	Combined robotic and endonasal approach	Improved visualization and precision in nasopharyngeal stenosis repair	Single-case experience only

DISCUSSION

Robotic surgery has rapidly evolved into a pivotal innovation in head and neck surgical practice, with a growing body of literature supporting its safety, feasibility, and functional advantages. The studies reviewed in this article collectively underscored the transformative potential of robotic systems—particularly transoral robotic surgery (TORS)—in overcoming anatomical limitations, enhancing visualization, and minimizing morbidity in complex surgical fields. Through technological advances, novel platforms, and conceptual integration with artificial intelligence (AI), the scope of robotic surgery continues to expand beyond oncologic resection to include neck dissection, pediatric applications, and hybrid procedures.

Several studies contributed robust evidence supporting the feasibility and clinical safety of robotic surgery across diverse institutional settings. For instance, Sommerfeldt et al.[14] demonstrated that TORS using the Da Vinci Xi system could be implemented safely even in low-volume centers without compromising surgical outcomes. Similarly, Dabas et al.[12] reported favorable oncologic and cosmetic results from robotic-assisted neck dissections via the modified BABA approach, emphasizing both functional preservation and patient satisfaction. These findings collectively validated the utility of robotic systems in routine head and neck oncology when appropriately applied and supported.

New platforms such as the Versius system and KD-SR-01 represent a significant shift toward greater accessibility and affordability. Agne et al.[4] showed that the Versius platform is both trainable via simulation and feasible in human procedures, while Ma et al.[13] confirmed that the KD-SR-01 achieved comparable hemostasis and reduced cognitive workload in preclinical trials. These developments might play a crucial role in democratizing robotic access in low-resource settings, a persistent limitation noted in both clinical and survey-based reports.[6,13]

Despite these encouraging findings, the literature also revealed considerable variability and several unresolved controversies. A prominent concern was the high cost of robotic systems, which remained a significant barrier to widespread adoption, especially in public healthcare systems and developing countries.[6,13] Although newer platforms promised cost reductions, comparative economic analyses were lacking. Moreover, while some studies emphasized the effectiveness of simulation-based training and robotic learning models,[2] others highlighted inconsistent access to training opportunities and a lack of standardized curricula, particularly among early-career surgeons.[4,6]

Theoretical enthusiasm for AI-enhanced robotics also presents a gap between conceptual promise and clinical application. While Sriram et al.[3] and Wojtera et al.[9] outlined the integration of AI in surgical decision-making and automation, no study provided empirical validation of AI-enhanced surgical workflows in clinical settings. This disconnects signals the need for translational research to move beyond modeling and towards implementation and outcome analysis.

Importantly, these technological and clinical developments carry profound implications for medical education and policy. Robotic surgery demands a reconfiguration of surgical training programs to include robotic platforms, simulation models, and exposure to AI-integrated systems. Policies should promote investment in infrastructure and surgeon education, especially in low- and middle-income regions. Additionally, credentialing and competency assessment will require revision to align with the evolving skill set required for robotic proficiency.

Unanswered questions persist across multiple domains. Clinically, high-quality, multicenter randomized controlled trials

(RCTs) are still needed to assess long-term outcomes, especially in pediatric populations, and for newer platforms.[10] From a system perspective, more work is needed to understand how robotic surgery can be sustainably integrated into healthcare delivery, without exacerbating inequalities in access.[6,13] Technologically, AI-enhanced robotics must progress from theoretical potential to tested, validated tools in operative environments.[3,9]

For future developments research should prioritize: comparative trials of robotic platforms (e.g., Versius vs. Da Vinci vs. KD-SR-01); Cost-effective studies assessing short- and long-term healthcare impact; Training research focused on standardized curricula, simulation efficacy, and credentialing pathways; Clinical integration of AI, including decision-support tools and real-time intraoperative assistance; and expansion of robotic applications into underrepresented populations such as pediatrics,[6] low-resource centers,[9] and emerging subspecialties (e.g., skull base surgery).

By addressing these areas, the field could move toward more equitable, evidence-based, and technologically integrated surgical care in otolaryngology and head and neck surgery.

In conclusion, this review was meant to evaluate the impact of robotic surgery in head and neck procedures, and the objective had been met. The findings confirmed that robotic approaches, especially transoral robotic surgery (TORS) and robotic neck dissection, were clinically feasible and offered favorable outcomes across diverse settings. Emerging platforms like Versius and KD-SR-01 showed promise in improving accessibility and reducing cognitive load, though they required further validation. However, challenges remain, including high costs, inconsistent access to training, and a lack of randomized controlled trials. While artificial intelligence is widely discussed for its potential to enhance surgical planning and automation, it has not yet been integrated into routine clinical practice. Overall, robotic surgery in head and neck care is advancing steadily, but requires strategic investment in research, education, and infrastructure to fully realize its potential.

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