Lasers and Robots: Recent Developments in Transoral Laser and Transoral Robotic Surgery

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Transoral microsurgery has come a long way as a go-to surgical intervention technique for head and neck cancers. This minimally invasive procedure had gained acceptance through comparative clinical studies against radical neck surgical procedures, radiotherapy, and chemotherapy. Laser technology has vastly improved the oncological outcomes of this procedure and brought about an appreciation of transoral laser surgery (TLM) as a mainstay for re-sectioning malignant tumors along the throat. As an established procedure, TLM has undergone several upgrades regarding the different energy devices used for cutting, ablation, and hemostasis. Continued advances in automation have eventually led to surgical robotics, resulting in the emergence of transoral robotic surgery (TORS) as a viable advanced alternative for TLM. Similarly, expansions and enhancements (image-based guidance, fluorescence spectroscopy, and advanced robotic system) have also been investigated as potential upgrades for TORS. This paper reviews a selection of publications on the significant technological advancements to TLM and TORS over the past five years.

Key words

Transoral surgery; Laser; Robot; Cancer

Received October 11, 2020
Accepted November 24, 2020

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INTRODUCTION

Abnormal and uncontrolled growths occurring below the skull base and above the collarbone are classified as head and neck cancers. These type of malignant growths covers a wide classification which includes carcinomas, lymphomas, and sarcomas typically found along the neck region. Squamous cell carcinomas of the upper aerodigestive tract represent approximately 90% of these cancerous growths. These tissues are highly delicate and are particularly difficult to replace which in turn complicates the treatment of cancerous growths along with its anatomical location. Several specializations, which include oncology, pathology, radiology, head and neck surgery, and speech therapy, are brought to effectively resolve these types of harmful growths and manage post-operative conditions of patients.¹⁻⁵

As with all other types of diseases, early detection offers the best chance for successful treatment of head and neck cancers. These types of cancers, when properly diagnosed in its early stages, can be approached with less invasive surgery which often offers the best results with regards to organ preservation and outpatient management.

A number of treatments have been established to circumvent the complexity of treating head and neck cancers. Previous customary approaches were focused on the excision of the tissue or organ afflicted by malignant growth. Decades of research have provided other organ-sparing techniques to remedy head and neck cancers. Progress in the different radiological, oncological, and less invasive surgical procedures provided some promising results dependent on the stage of the cancer being treated.¹

Until the first half of 1900, open surgery, radiation, and chemotherapy have been the choice for the various types of head and neck cancers. Technological advancements in surgical optics, robotics, and laser technology have laid the foundation for the maturation of less invasive surgical procedures. The transoral approach was intended to maximize the result of surgical removal of cancerous growth by minimizing drastic tissue dissection and anatomical disruption along the cervical area of the patient. Mandibular retraction is no longer required since the surgical sites are accessed through the oral cavity. Originally limited to malignant growths that can be directly observed and operated on with standard instrumentation and lighting, improvements in technology has been incorporated to expand the reach and capabilities of transoral surgery.

Transoral laser microsurgery (TLM) and transoral

robotic surgery (TORS) are two of the technologically advanced procedures derived from endoscopic transoral surgery. These minimally invasive surgical procedures for treating head and neck cancers have gained recognition due to the relative conservation of organs and reduce collateral tissue damage. Both TLM and TORS are emerging techniques that are meant to take advantage of the growing knowledge of energy and robotics. This article will be discussing the brief histories of TLM and TORS and surmise the potential evolution of transoral procedures in reference to selected articles published in the past five years.

TRANSORAL LASER MICROSURGERY (TLM) AND TRANSORAL ROBOTIC SURGERY (TORS)

Advancements in surgical lasers, binocular microscopy, and recognition that tumors along the upper aerodigestive tract can be fractionally excised led to the development of transoral laser microsurgery (TLM) in the 1960s and 1970s. TLM has been a proven effective procedure for resolving the early stages of oropharyngeal cancers. The basic TLM setup is composed of a retractor or laryngoscope, binocular operating microscope, microlaryngeal instruments, and a laser delivery device (commonly carbon dioxide laser (CO₂) laser).⁶

Moisture at the tissue readily absorbs CO₂ lasers which are transformed into thermal energy allowing for precise incisions. Lasers can also be used for tissue ablation and photocoagulation through proper adjustment of the focal length. Further control on laser shape, power, spot size, duration, pulse, and beam pattern has become available in advance setups coupled with a computer system.^{6,7} Other types of energy devices have been tested under TLM practice which will be discussed in the succeeding section.

One characteristic disadvantage of TLM is the delivery of the laser along a linear path within the range of line-of-sight. Incisions or ablations cannot be performed on locations beyond the visible field since the laser device cannot go around corners. Proven protocols for TLM have lessened the difficulties associated with errant laser beams, steep learning curve, and potential burns of exposed body parts.

Robots have been utilized in the surgical theatre as early as the 1980s and several systems have already been approved by the FDA which includes the Transoral Robotic Surgery (TORS) back in 2009.^{8,9} This surgical robot system is composed of four main parts; the surgeon console that relays user inputs; articulated robotic endowrist

tools for tissue manipulation; visualization system that provides real-time imaging of the surgical site; and the patient cart.^{6,7}

The video endoscope provides a three-dimensional view of the surgical site and the robotic tools within the oral access of the patient. TORS operates under a “master-slave system” wherein the movement and manipulation of the robotic arms and tools are accomplished through surgeon input relayed by the console.^{6,7} The robotic system offers significant advantages over traditional TLM. The visualization system can provide high-resolution 3D perspective that aids in navigating otherwise inaccessible locations. It imparts improved degrees of motion with respect to the maneuverability of the robotic tools. It imparts precision movement with minimal tremor-infiltration associated with traditional hand-held instruments. Considering that TORS is a relatively emerging practice, it is not without some disadvantages. The primary consideration for adaptation of TORS is the cost of the robotic system and the credential validation requisite for surgeons.

ENERGY DEVICES FOR TLM AND TORS

Early versions of transoral surgery included an electrocautery device for incisions and hemostasis. These monopolar or bipolar energy devices have long been replaced by one of the earliest gas lasers to be developed which remains to be the most widely adopted for various applications: the CO₂ laser. Electrocautery has poor depth control and low precision thus collateral thermal tissue damage has been a major issue due to its undesirable effect on the healing and integrity of surrounding tissues.¹⁰⁻¹²

Carbon dioxide lasers offer the same cutting and coagulation capability whilst mitigating the effects of severe collateral thermal tissue damage. Owing to its well-documented efficiency and cost-effectiveness, laser technology is now being considered to be integrated with TORS which could further enhance the capabilities of the robotic system. This is made possible through the development of fiber optic CO₂ lasers.⁶ Delivery of the CO₂ gas laser beam can now be accomplished around anatomical corners through flexible fiber optics under 3D visualization.

In addition to the use of CO₂ gas laser, solid-state diode lasers have also been investigated for their potential use in transoral surgery.^{11,13-17} The limitations of CO₂ laser, namely field of view constraints, narrow penetration, and cost, prompted the investigation of using other lasers like KTP (potassium titanyl phosphate) and dual-wavelength optic fiber laser. Compared to CO₂ laser, KTP laser has

been found to have superior coagulative capability and greater penetration.

KTP laser is primarily absorbed through the red spectrum making it suitable for the ablation of highly vascularized malignant tumors wherein high amounts of hemoglobin is present.^{11,14} Due to its angiolytic property, it has been suggested that KTP be used as an ablative technique that can be used to eliminate cancerous tissue while preserving vocal functionality.

Another type of laser that has gained attention for application in TLM is a dual-wavelength laser diode.¹⁶ This technology offers a unique two-in-one energy device that is capable of hemostasis and incision designed to operate in tight spaces. In addition to the angiolytic and superior hemostatic ability, solid-state diode lasers are more power-efficient and are readily adapted for fiber optic delivery making them suitable add-ons in TORS.

Aside from laser-based energy devices, radiofrequency ablation (RFA) have also been utilized for transoral microsurgery.^{18,19} This technique is performed by inserting a needle probe for deploying tines into the tumor mass. Half of the tines are electrodes for delivery of radiofrequency current while the remaining tines are thermocouples for monitoring temperature. Upon delivery of radiofrequency, ionic molecules present in the tumor begin to vibrate and heat up. Tumor necrosis is induced through hyperthermia ranging from 60-110°C.

A recent study has proven RFA to be advantageous compared to CO₂ TLM for treating glottic cancer.¹⁹ Benefits of using RFA include improved infiltration depth into the tumor mass, enhanced probe maneuverability allowing for improved ablation or resection, ease of operation, faster recovery, and low energy consumption. The low thermal efficiency of RFA compared to other techniques makes it less effective when presented with intraoperative bleeding and would require secondary hemostatic intervention.¹⁸ The determination of safety margin is also a concern but can be resolved with multi-modal visual guidance. Table 1 summarizes the advantages and disadvantages of the different energy devices used for TLM and TORS.

INNOVATIVE IMAGING SYSTEMS FOR TLM AND TORS

Numerous modes of visualization offer an immense opportunity for proper planning and staging of cancer surgeries. Conventional technology mostly renders static representations of the target anatomy. The innovation of machines capable of live imaging has presented great

Table 1. Comparison of energy devices used in transoral laser microsurgery and transoral robotic surgery

Energy device	Advantages	Disadvantages
Electrocautery	<ul style="list-style-type: none"> • Provides capability for cutting and hemostasis • Comparable healing results with scalpel blade • Reduced post-operative pain 	<ul style="list-style-type: none"> • High working temperature (450-600°C) • Carbonized debris • Irregular incision borders • Lateral heat damage
Carbon dioxide laser	<ul style="list-style-type: none"> • Shorter operating time • Provides capability for precision cutting • Hemostatic • Minimal lateral tissue damage 	<ul style="list-style-type: none"> • Requires extensive training and safety precaution • Requires venting for gas medium • Narrow tissue penetration • Higher operating cost • No haptic feed back
Solid state laser	<ul style="list-style-type: none"> • Shorter operating time • Provides capability for precision cutting • Hemostatic • Does not require venting for gas media • Deeper tissue penetration • Power efficient • Dual wavelength operation 	<ul style="list-style-type: none"> • Requires extensive training and safety precaution • Minimal haptic feed back • Risk of over penetration
Radiofrequency ablator	<ul style="list-style-type: none"> • Lower working temperature (40-70°C) compared to lasers • Minimal surrounding tissue thermal collateral tissue damage • Faster healing and reduced post-treatment pain • Minimal scarring 	<ul style="list-style-type: none"> • Requires extensive training • Risk of bleeding though over / mis-penetration of probes • Requires deep tissue imaging during procedure

prospects for improving visualization, particularly in endoscopic and robotic surgery. This section will present some of the advancements in imaging system currently being harnessed for transoral surgery.

Proper examination of preoperative imaging is the key to surgical staging and navigating critical anatomy during transoral surgery. Tomography is one of the cornerstone imaging technique sought after for identifying surgical margins for tissue resection under TLM and TORS. Nevertheless, surgeons are left to rely mostly on experience to remain adequately oriented even after tissue deformation and loss of landmarks brought about by the procedure and/or the patient's posture.

To address this issue, two recent studies were carried out to test the feasibility of a workflow for integrating preoperative imaging and intraoperative imaging as a visual guide during transoral robotic surgery. The first study concentrated on computed tomography (CT)²⁰ while the follow-up study included the use of magnetic resonance imaging (MRI).²⁰ Both studies processed scans of porcine and human subjects to render volumetric segmentation of the target tissue mass for excision. Image and volume registration (with ascertained landmarks) were conducted across both imaging data gathered from normal preoperative CT/MRI and intraoperative CT. The initial rigid image registration was then processed with an algorithm that transforms cross-registered imaging data into deformable registration. The resulting deformable image regis-

tration data was then uploaded unto the TORS to calibrate the stereo endoscope for enhancing image guidance during surgery.^{20,21} Although the current workflow is quite complicated and requires intensive focus, the results indicated that deformable image registration provides highly useful data for intraoperative mapping during TORS.

In another study, optical coherence tomography (OCT) was tested for verifying tumor depth invasion during TORS. Optical coherence tomography uses near-infrared light reflected from the optical interfaces of tissues.²² This can be used as preoperative or intraoperative imaging to visualize the layers and verify the depth of tumor invasion at higher resolution compared to CT or MRI. The report indicates that OCT is a useful tool for both diagnoses and can be considered as a valuable tool for TORS.

An additional technique for real-time identification of cancerous growth during transoral surgery makes use of fluorescence lifetime imaging (FLIM) observed through and intraoperative fluorescence spectroscopy.^{23,24} This type of enhanced intraoperative visualization takes advantage of the autofluorescence capabilities of the tissues to distinguish malignant and premalignant tissues from surrounding tissues. Using a modified robotic arm containing a multimode fiberoptic, an excitation laser is delivered to the tissue region to induce autofluorescence of porphyrins, Nicotinamide adenine dinucleotide phosphate (NAD(P)H), and flavin adenine dinucleotide (FAD). The emitted autofluorescence is gathered using the same

fiber optic and then spectrally resolved through a wavelength selection module. The resolved fluorescence is then amplified and time-resolved to detect real-time fluorescence decay.^{23,24} With this method, cancerous tissues can be identified without the application of exogenous probes and the re-sectioned sites can be intraoperatively examined for remaining tumors post-extraction.²³⁻²⁵ Although FLIM can provide an effective means of detecting cancerous tissues based on changes in the molecular composition of cells, the study has found that several factors can affect this type of image guidance. Among the factors that could affect FLIM under TORS are tissue diversity, thickness of the epithelium, cancer cell type, removal method (laser or electrocautery), and presence of bleeding.

Narrowband imaging (NBI) is one of the most notable advancements that has accompanied technical improvements in digital image processing. This technology enables enhanced visualization of tissue vascularization. By activating a filter that restricts the detectable ambient light to blue (415 nm) and green (540 nm), blood vessels appear darker.²⁶⁻²⁹ This is because hemoglobin peak light absorption is limited along these wavelengths which in turn enhances the contrast of highly vascularized structures. This technology is already available for endoscopes and is currently being evaluated for integration into robotic surgery setups. The high-contrast visibility enables identification of tumorous growth during minimally invasive explorative diagnosis and better delineation of surgical margins during TLM^{27,28} or TORS²⁶ procedures.

Developments in computer graphics have enabled the integration of data based virtual information with real-time video feeds. Previously discussed studies on deformable CT registration and FLIM were carried out with

augmented reality (AR) in mind.^{20,21,23,24,30} These imaging techniques were designed to overlay visual information on the endoscopic video feed. The deformable CT imaging is integrated into TORS as a means to visualize the target tissue within the three-dimensionally mapped out the surgical site. On the other hand, FLIM was designed as a graphic overlay that shows the intensity and gradual decay of autofluorescence of endogenous molecules in the tissue surface. Both technologies are applied as AR under TORS and are capable of continuous visual information update in accordance with the dynamic nature of the procedure.³⁰ Granting that AR is a highly sought-after visual enhancement, the software for processing preoperative imaging data still needs significant improvements.

NEXT-GENERATION ROBOTIC SYSTEM

Superior miniaturized flexible armatures have also been given way into successfully developing a robotic system capable of a single port approach during laparoscopic surgery. This technology has also been highly adapted for transoral surgery through TORS. Initial development of small flexible tools was brought about the limitations of the previously rigid types of instrumentation adapted for early TLM technique. The system, dubbed "FLEX", is composed of a highly articulated snake-like arm with inner and outer sleeves concentrically arranged as a segmented mechanical tool.³¹⁻³⁵ This flexible arm houses a high definition video feed and is accompanied on its sides with instruments of similar base design. Motion and manipulation of the FLEX robotic system is relayed from a console with joystick inputs from a surgeon. Similarly, another company has also developed a more advanced system which also makes use of highly articulated snake-

Fig. 1. Schematic outline of technological improvements in TLM and TORS from the past 5 years.

like robotic arms. The single-port robotic (SP-R) system was developed as a ubiquitous robotic laparoscopic surgical system intended to replace traditional multiport surgical techniques. Compared to the FLEX, the SP-R system was designed to access the surgical site via a single opening while providing a greater number of instrumentations. The SP-R is composed of a smaller highly articulated endoscope and three similar-sized reconfigurable robotic arms.^{36,37} Both robotic systems have undergone clinical studies and have been proven effective for diagnostic and transoral cancer surgery.^{34,36,37} These robotic systems used for TORS are currently commercially available, allowing third party institutions and medical practitioners to further study the possible add-on technologies.

CONCLUSION AND FUTURE OUTLOOK

While knowledge on cancer as a disease and treatments continuously evolve into a more systematic and customized approach, technological advancements in the field of surgery drastically change how surgeons' approach and operate. This has become more evident in procedures such as TLM and TORS in the past decade. Fig. 1 shows the changes and enhancements presented in this article. Although novelties in this field are far in between, the technologies that have been tested are highly interesting and adaptable. Based on current literature, TLM could eventually be replaced by TORS as a mainstay for treating head and neck cancers. Integration of lasers and other energy devices for tumor mass resection and the addition of improved real-time visualization and diagnostic imaging in TORS would eventually overshadow the simplicity of the TLM setup. Lasers, on the other hand, has found a new purpose under TORS. Instead of being utilized as a tool for tissue manipulation, lasers have become a device for intraoperative tissue analysis. This promotes the rationality of combining robotic surgery with laser technologies. Currently, robotic laser surgery is constrained by expensive hardware, limited opportunities for training, and under-developed software. These obstacles can only be settled with continuous research, testing, information dissemination, and practice validation. As society moves deeper towards the digital age, robotic laser surgery would inevitably become commonplace as it consolidates the distilled knowledge from several fields of sciences as a safe and practical solution.

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How to cite this article: Padalhin AR. Lasers and robots: recent developments in transoral laser and transoral robotic surgery. *Med Lasers* 2020;9:103-109. <https://doi.org/10.25289/ML.2020.9.2.103>