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Original Paper

Next-Generation Robotic Head and Neck Surgery

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Abstract
Following the inception of transoral robotic surgery (TORS) in 2005, the field of robotic head and neck surgery has undergone refinement and innovation. Optimizing patient outcome, preserving function, and limiting morbidity are the key drivers. The next leap forward is another generation of flexible robotic surgical systems. Several such systems are under clinical and preclinical evaluation. A new single-port (Sp) robotic surgical architecture is now available integrating three fully articulating instruments and a flexible three-dimensional high-definition camera delivered through a 25-mm cannula. Preclinical feasibility studies of the Sp in human cadaver and porcine models suggest improved application compared to existing platforms for oropharyngeal and nasopharyngeal resection. With 3-handed manipulation of tissue, traction and countertraction may be used to deliver a more precise surgical dissection of head and neck anatomy than is currently possible. The single-port design permits greater access and maneuverability for the bedside surgical assistant. An alternative currently available in clinical use includes the Flex® system using a robotic camera and manually controlled endoscopic instruments. The Cambridge Medical Robotics Versius system is undergoing preclinical evaluation for TORS and may offer a novel modular approach. All of these systems allow the head and neck surgeon to reach further beyond the upper aerodigestive tract with greater agility and precision, expanding the boundaries of minimal access head and neck surgery.

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Head and neck surgery is experiencing an evolution akin to that of traditional open abdominal and pelvic procedures, giving way to laparoscopic and natural orifice surgery. This evolving surgical paradigm is fueled by the desire to preserve function and limit surgical morbidity through minimally invasive approaches. In the era of contemporary head and neck surgery, transoral endoscopic techniques provide access to the pharynx through the natural orifice of the mouth. Surgeons can now use a variety of new technologies to resect early and intermediate-stage cancers using an "inside-out" surgical approach [1]. First-generation robotic surgical systems demonstrated the feasibility of robotics within head and neck surgery but were constrained by configurations poorly suited to the unique anatomy of the pharynx and larynx. Next-generation flexible robotic systems will accelerate innovation and help facilitate the true emergence of robotic head and neck surgery.

The morbidity of open surgical procedures of the early 20th century provided the major impetus for the development of less-invasive approaches. Endoscopes and advances in surgical instrumentation gave rise to laparoscopic surgery. Most of the earliest experience with robotic surgery was in laparoscopic applications starting in the late 1980s. A major leap forward came in 2000 when Intuitive Surgical's da Vinci® surgical system became the first robotic platform approved by the Food and Drug Administration for general laparoscopic surgery (Intuitive Surgical Inc., Sunnyvale, CA, USA). Multiple small access ports with rigid instrument arms following linear trajectories provided surgeons minimally invasive robotic access to the depths of the abdomen. Finely tuned instrument control allowed them to safely operate with precision and accuracy.

Transoral robotic surgery (TORS) originated in 2005 with seminal work in canine and cadaver models [2, 3]. This opened the door to early adopters in robotic head and neck surgery who helped pave the way for approval and more widespread acceptance. In 2009, the US Food and Drug Administration approved the da Vinci® surgical robot for resection of T1–T2 cancers of the oropharynx, larynx, and hypopharynx [4]. Numerous advances and refinements by a handful of innovators have collectively helped to advance the field of robotic head and neck surgery to our present level [5].

Today, the treatments of benign and malignant pharyngeal diseases are the most common indications for TORS. Notably, TORS has also been successfully applied to diseases of the supraglottis, glottis, hypopharynx, parapharynx, and nasopharynx. Currently, only multiarm robotic systems are available from Intuitive Surgical (da Vinci® S, Si, and Xi models). Today's robotic head and neck surgery procedures are sure to evolve through continued growth and refinement, but the most exciting advances may emerge through a quantum leap in the capabilities of next-generation flexible surgical robots. Two systems show particular promise in this regard; the da Vinci® Sp (single-port) system and Cambridge Medical Robotics Versius system. Both systems share similar features in reducing the working footprint whilst expanding transoral minimal access capability. The Versius system is undergoing preclinical feasibility evaluation, and therefore the focus of the remaining sections will be the da Vinci® Sp (single-port) system.

The current da Vinci® robotic systems are well suited for laparoscopic surgery applications. In the abdomen and pelvis, laparoscopic instrument triangulation occurs across distances of many centimeters. Multiple robotic instrument arms can be separately docked to approach the working space from wide angles. Significant hurdles occur when a laparoscopy-based robotic platform is applied to head and neck anatomy. The oral aperture narrows the angles of robotic arm access, and confined operative fields add to the challenges. With today's multiarm robotic systems, separate bulky instruments converge on the operative field but their wide-angle trajectories clutter the working space outside of the oral cavity resulting in major limitations for head and neck surgery: availability of only 2 working instruments, impaired surgical assistant access, and restricted anatomical reach.

Fig. 1. da Vinci® Sp patient-side cart (Intuitive Surgical Inc., Sunnyvale, CA, USA).

In multiarm robotic head and neck surgery of today, only 2 of the 3 available working arms are utilized because there is no additional room to maneuver the third robotic instrument arm. One instrument is used to grasp tissue, providing tension, while the other instrument is used for dissection. The main working instrument is usually a monopolar spatula or bipolar instrument.

The single-port (Sp) system was designed with head and neck anatomy in mind. It has flexible camera and instrument arms that enter from a single port and deploy within the surgical field. The Sp delivers 3 serpentine robotic instruments to the surgical site, expanding the possibilities beyond what is possible with current 2-instrument systems. The addition of a working instrument brings multiple possibilities to the surgeon for simultaneous traction, countertraction, and dissection.

The bedside surgical assistant is frequently called upon to suction, retract, and apply vessel clips. Multiarm robotic systems significantly limit the available working space for this assistant, while a single-port architecture may be readily maneuvered around, improving access for a surgical assistant, and for shared airway management with the anesthesia provider. The surgical assistant is sure to encounter new challenges when working deeper in the upper aerodigestive tract, but having more space to maneuver around the robot will help greatly.

Perhaps the most significant drawback of current robotic systems is their restricted anatomical reach. Compared to laparoscopic applications, the head and neck has smaller triangulation angles and necessitates a device capable of maneuvering in a more compact spatial geometry. By changing the robotic configuration to now use a single port of access for the camera and working arms, these deeper sites are more accessible than ever before. As transoral access to subsites beyond the oropharynx becomes easier, we are likely to see an expansion of TORS indications and usage.

Safety of the Sp was established using an early single-port system through a human phase II trial in urological surgery [6] and, since then, the single-port robot has undergone preclinical testing and clinical evaluation for head and neck surgery. Feasibility studies with cadaver models for oropharyngectomy, tongue base resection, and nasopharyngectomy have promising results with encouraging capabilities [7–9]. In these early studies, docking the da Vinci® Sp patient-side cart (Fig. 1) at the operative table was straightforward. The single arm could be moved 270° around its central axis so that the angle of approach could be optimized. There was more room for a bedside surgical assistant to work (Fig. 2). We have additional preclinical

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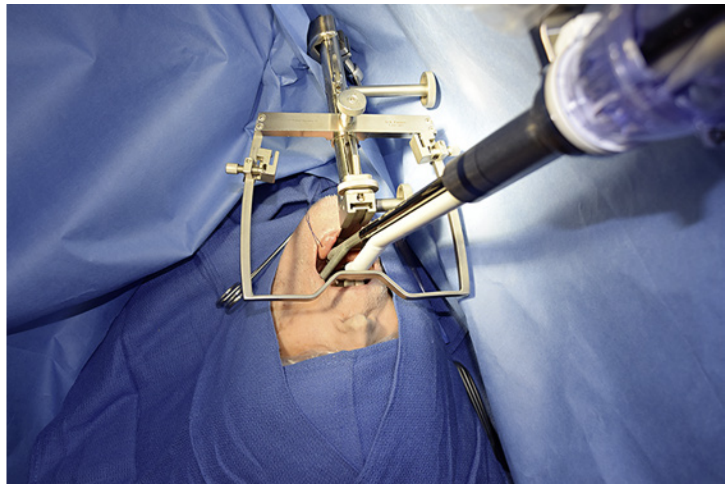

Fig. 2. da Vinci® Sp docked for oropharynx approach (Intuitive Surgical Inc., Sunnyvale, CA). Oropharynx retraction with FK-WO retractor (Olympus). Ample space around the patient's face is available for the bedside surgical assistant.

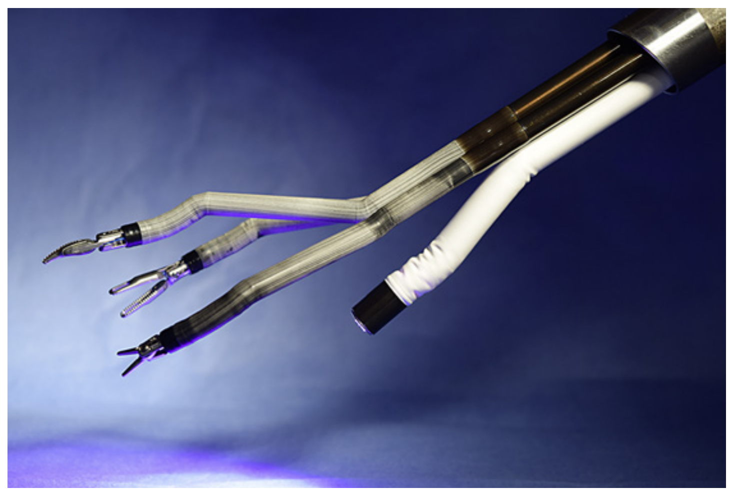

Fig. 3. da Vinci® Sp cannula with 4 channels. Articulating camera and 3 instruments deployed (Intuitive Surgical Inc., Sunnyvale, CA, USA).

experience with transoral supracricoid laryngectomy, and retroauricular thyroidectomy and neck dissection. The first 6 human cases of TORS with the da Vinci Sp were reported [10], and clinical trials with the Sp are ongoing in the USA.

In addition to docking considerations, the addition of a third operative instrument will require us to change the way we think about and perform robotic head and neck surgery. Refinements to the patient-side cart docking, patient positioning, instrument and camera configuration, and technique will surely come through continued innovation. For example, rethinking our patient position and exploring upright patient positioning may improve access to the inferior pharynx and larynx, and expand patient candidacy for TORS [11].

The single arm of the da Vinci® Sp is comprised of 4 channels that pass through a single 25-mm stainless-steel cannula port. One of the channels houses a zero-degree binocular stereoendoscope that can be independently maneuvered to provide 0–30° of angulation (Fig. 3). Controlling the camera angulation allows the surgeon to constantly optimize the visualization and obviates the need to swap camera instruments. This advanced endoscope provides 3-dimensional visualization in high definition.

The other 3 channels carry 6-mm instruments, thus allowing 3-instrument surgery as opposed to traditional 2-instrument TORS. Early on, an array of instruments will be available (Fig. 4), and additional specialized instruments may also be developed. With the aid of a

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Fig. 4. da Vinci® Sp instrumentation. A variety of instruments will be available for the da Vinci® Sp system including energy devices (bipolar and monopolar instruments), needle drivers, grasping instruments, and clip appliers.

surgeon at a second robotic console, all 3 instruments can be controlled simultaneously. This third instrument can be continually adjusted to change the vector of pull with the use of the instrument swap pedal. With the addition of one working instrument, TORS procedures may benefit from better surgical plane manipulation through traction and countertraction. Mucosal folds that would otherwise be tented or collapsed in traditional 2-arm TORS can now be retracted and better exposed. Expanded maneuverability in tissue manipulation may result in better hemostasis and margin control rates.

Sp instruments can work within a surgical space the size of a tennis ball, golf ball, or smaller, depending on anatomical constraints. The surgeon controls the instruments within that space, and can move and manipulate tissues independently of the robot arm itself. The camera port can be switched from the superior (camera above) to inferior (camera below) configuration, and the entire robotic arm can be rotated during the dissection.

Several modes of endoscope camera and instrument manipulation are available. In "relocate mode," the instruments and the camera move together, with gross motion of the entire single-port robotic arm. This mode is not necessary in most robotic head and neck surgical procedures because the surgical area is spatially constrained and relatively static. In "adjust mode," the instrument working ends (graspers, monopolar tip, etc.) maintain their orientation with the tissues while the robotic cannula vector is changed. To accomplish this, the instrument elbows (joggle joints) adjust for the motion of the robotic arm. When the joggle joints have reached the limit of their flexibility, an alert is signaled on the graphical user interface and further robotic arm excursion in the applicable direction is restricted (Fig. 5). The camera can also be independently maneuvered around a fixed surgical space (camera mode).

Though the way that the da Vinci® Sp will fit into the armamentarium of the contemporary head and neck surgeon is yet to be defined, the collective innovations of this next-generation platform open the door for exciting possibilities. In addition to more facile oropharynx resection, the larynx will be more accessible. Supraglottic and even supracricoid partial laryngectomy procedures can be performed. Tumors and benign disorders of the hypopharynx may also be treated with next-generation systems. The challenging exposure and manipulation required for cricopharyngeal myotomy and Zenker's diverticulotomy may become easier, and advances in nasopharyngectomy and skull base robotic approaches are likely to follow.

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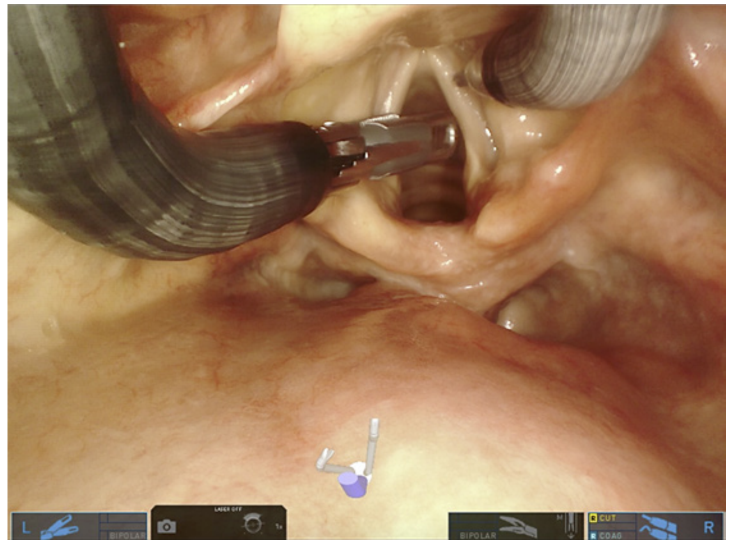

Fig. 5. da Vinci® Sp graphical user interface (Intuitive Surgical Inc., Sunnyvale, CA, USA). The 3-dimensional operative image is visible to the surgeon (2-dimensional image here). The schematic in the middle-lower portion of the screen displays the camera and instrument arm configuration.

In the future, one could even foresee the implementation of next-generation systems into tele-robotic surgery applications such as collaborative surgeries, combat settings, remote locations, and in other scenarios where surgical expertise needs to be disseminated over a broad geographic footprint. There are considerable logistic, validation, and medicolegal barriers to this application, but the rapid advances that we have witnessed in the past decade make this vision believable and attainable. Progress toward these applications has been ventured using the current da Vinci® models, and the single-port system may be an exciting next step in this progression. Additional creative applications for robotic head and neck surgery are also being explored – for example, the robot could be docked across the operative table from an assistant in an open surgical field and used to assist with fine maneuvers such as microvascular surgery.

Another approach to minimally invasive head and neck surgery is the hybrid approach of the Flex® system (Medrobotics Inc., Raynham, MA, USA). Flex® relies upon a novel combination of two instruments manually controlled by the surgeon, yet utilizing a fully robotic snake arm monocular robotic camera. Since these instruments are controlled by the surgeons' hands, rather than by a remote robotic system, manual haptic feedback and tactile sensation are preserved, which may provide an advantage to surgeons. This system can be regarded as more akin to a laparoscopic platform that may offer a simpler and more affordable system to many surgeons and hospitals. Its role and potential advantages in head and neck surgery remain to be fully defined.

The Versius Cambridge Medical Robotic System is the latest next-generation flexible robotic system to reach the threshold of CE marking and is more akin to a robotic platform. The system is of a modular design purported to be more cost effective than the existing commercial systems available on the market.

Future innovations in hardware and software may push the envelope even further beyond the systems described above. Materials and mechanical engineering advances will bring stronger, more agile instrumentation. Fluorescence imaging technologies and machine-learning image processing will change the way that we see tissue interfaces and detect oncological margins. Semiautonomous robotic behaviors may even become interwoven with our maneuvers to streamline tasks and increase the efficiency and precision of our surgeries. This departure from the conventional master-slave configuration is sure to raise ethical and medicolegal issues but may improve the efficiency, safety, and quality of robotic surgery.

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Technological refinements of next-generation robotic surgical systems, as discussed in this paper, represent significant conceptual and mechanical improvements that will likely advance robotic head and neck surgery in the years to come, facilitating surgery of the larynx, reconstructive procedures, and advanced telesurgical collaboration. Robotic surgery is a rapidly expanding field in which the most rigid limitations of what can be done are, in fact, those restrictions placed by our imaginations.

Disclosure Statement

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