Potential applications of the da Vinci minimally invasive surgical robotic system in otolaryngology

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Abstract

Anatomic constraints and instrumentation design characteristics have limited the exploitation of endoscopic surgery in otolaryngology. The move toward less invasive and less morbid procedures has paved the way for the development and application of robotic and computer-assisted systems in surgery. Surgical robotics allows for the use of new instrumentation in our field. We review the operative advantages, limitations, and possible surgical applications of the da Vinci Surgical System in otolaryngology. In the laboratory setting, we explored the setup and use of the da Vinci system in porcine and cadaveric head and neck airway models; the setup was configured for optimal airway surgery. Endoscopic cautery, manipulation, and suturing of supraglottic tissues were performed in both the porcine and cadaveric models. We found that the da Vinci system provided the advantages of the lower morbidity associated with endoscopic surgery, more freedom of movement, and three-dimensional open surgical viewing. We also observed that the system has several limitations to use in otolaryngology.

Introduction

Advances in surgery have centered on minimizing the invasiveness of surgical procedures as a means to reduce patient morbidity and mortality. As a result, improvements in video imaging, endoscopic technology, and instrumentation have made minimally invasive endoscopic surgery the cornerstone of modern airway and sinus surgery. More recently, this technology has been explored for use in parathyroidectomy, thyroidectomy, and functional neck dissection, primarily to exploit its benefit in terms of postoperative cosmesis. Early reports have demonstrated that video-assisted thyroidectomy is a feasible and safe alternative to open thyroidectomy in selected cases; it is associated with an excellent cosmetic result and a significantly less painful postoperative course. Other realized advantages of endoscopic surgery through small incisions or natural orifices include lower infection rates and quicker recovery times.

The principal disadvantage of conventional endoscopic techniques is that freedom of movement is restricted. This restriction is attributable to (1) the confined operative field, (2) instrumentation’s limited ranges of motion, (3) a lack of three-dimensional imaging of the operative field (depth of field), and (4) a lack of haptic (tactile) feedback. In addition, working with traditional endoscopic instrumentation often leads to muscle fatigue, exaggeration of hand tremor, and imprecision attributable to the length of the instrument shaft and the higher handle forces.

The move toward less invasive and less morbid procedures and a need to re-create the true open surgical experience have paved the way for the development and application of robotic and computer-assisted systems in surgery. Robot-assisted surgical systems have already been used in humans to perform procedures in cardiac surgery (e.g., internal thoracic artery harvesting, mitral valve repair, and total endoscopic coronary bypass), general surgery (e.g., cholecystectomy, Nissen fundoplication, and inguinal hernia repair), urology (e.g., laparoscopic nephrectomy and radical prostatectomy), and gynecology (e.g., hysterectomy and tubal ligation reversal). Systems such as the minimally invasive da Vinci Surgical System (Intuitive Surgical; Sunnyvale, Calif.) have been shown to facilitate and improve the performance of endoscopic procedures.
The application of the da Vinci system in the laboratory set these current limitations. Robotics in otolaryngology may help overcome many of the technical challenges inherent to endoscopic surgery. The introduction of surgical instruments and techniques while maintaining the benefits of access through keyhole incisions. The da Vinci system's unique articulating laparoscopic EndoWrist instruments provide for seven degrees of freedom. Additional benefits include (1) three-dimensional viewing of the operative field with superb depth perception owing to the coaxial alignment of the eyes, hands, and tool-tip image; (2) motion scaling; and (3) tremor filtering, all of which increase precision.

Despite these recent advances, otolaryngologic endoscopic surgery is still limited by anatomic constraints and design characteristics of instrumentation that result in limited degrees of freedom. These factors have hindered the full exploitation of the new endoscopic surgery techniques in otolaryngology. The introduction of surgical robotics in otolaryngology may help overcome many of these current limitations.

Our goal was to explore the potential otolaryngologic applications of the da Vinci system in the laboratory setting. In this article, we discuss the operative advantages of the da Vinci system, its current limitations, proposed solutions to those limitations, and the system's potential applications in the field of otolaryngology.

Subjects and methods
After review and approval by the Walter Reed Army Medical Center Department of Clinical Investigation and the Animal Use Committee, we obtained two 65-kg domestic swine and one fresh human cadaver head and neck for study purposes in the laboratory setting. Our study was performed in accordance with our institution's policy on the humane care and use of laboratory animals and the Animal Welfare Act (7 U.S.C. et seq). The da Vinci system was used to perform endoscopic cautery, manipulation, and suturing of supraglottic tissues.

The da Vinci system is made up of three primary components: a surgical cart, a vision cart, and a surgeon's console (figure 1). The surgical cart is equipped with a robotic manipulator and three mounted arms; one arm holds the camera and the other two hold 8-mm instruments. The vision cart is equipped with two three-chip cameras mounted within an integrated, three-dimensional, 12-mm stereoscopic endoscope with separate optical channels. The surgeon's console displays stereo images obtained by the endoscopic camera; at this console, the surgeon controls the instrument arms and camera by maneuvering “master” robotic manipulators. According to other studies, the “master-slave” setup allows surgeons to perform more precise surgical manipulations than are possible during conventional endoscopic surgery.

The degrees of freedom with which the arms of the EndoWrist instruments operate include pitch, yaw, and roll plus two additional degrees of freedom in the wrist and two others for tool actuation—a total of seven degrees of freedom in all. Instrument tips are electronically aligned with the instrument controller stop and provide optimal eye-hand orientation and natural operative capability. The electronic motion scaling eliminates physiologic tremor. The swine were anesthetized and placed in a supine position. A tracheostomy was introduced via a midline incision. The animals were maintained on mechanical ventilation throughout the procedures. Following suspension laryngoscopy, the setup of the da Vinci system was undertaken. The location and setup of the system were established specifically for optimal airway surgery. Each instrument and camera arm has a remote center, which is a mechanically fixed point of rotation. Because each arm pivots around its remote center, careful placement was required to avoid applying unnecessary forces to the surrounding anatomy. The remote centers for the mechanical arms and three-dimensional endoscope were placed at various intervals within the snout, with 0 to 3 cm of separation. The surgical instruments were interchanged as required to perform atraumatic grasping, incision, cautery, and suturing of supraglottic tissue.

The human cadaveric thorax was fixed to the table to achieve 30° to 40° of neck extension. Suspension laryngoscopy was performed, and the da Vinci system was set up in a fashion similar to that used for the porcine model. The same procedures and instrumentation were employed. Additionally, during some maneuvers, the camera was held by a nonrobotic (pneumatic) Point Setter endoscopic arm (Karl Storz Endoscopy—America; Culver City, Calif.) rather than the da Vinci camera arm.

Results
Adequate access was gained through the oral cavity and oropharynx to allow for the performance of multiple tasks.
Visualization was excellent with both 0° and 30° three-dimensional cameras, which allowed for precise assessment and control of the instrumentation. Because of the length of the pigs’ snouts, we were unable to adequately use instrumentation in the area below the larynx. In an effort to familiarize ourselves with the operation of the instrumentation, we performed cautery, manipulation, and suturing of supraglottic tissues.

During our familiarization process, we became aware of several limitations to the use of the da Vinci system in the upper aerodigestive tract. The size of the instrument and the camera made it difficult to maneuver within the narrow confines of the oropharynx. Invariably, the instrument arms would abut one another and prevent complete freedom of motion. This occurred not only at the operative site, but outside the oropharynx as well.

Because the da Vinci system was designed for laparoscopic/thoracoscopic surgery, the instrument ports of entry are at divergent angles as they converge into the operative field. For our purposes, we maneuvered the robotic arms into “nonintuitive” positions, which required us to reposition them many times in order to achieve the optimal angle for introduction of the instrumentation. Because of this unique positioning, the instrument heads faced each other. By comparison, in cardiac valve procedures, which provide three widely spaced ports of entry into the abdomen or thorax. Because laryngeal surgery involves operating through a single confined natural orifice, we had to place all of the robotic arms in close proximity at the head of the operating table (figure 2). As a result, we experienced occasional external binding and interference of the large robotic arms. The size of the instrument manipulators (8 mm diameter) and the camera (12 mm diameter) exacerbated this problem by causing occasional internal binding and abutting of instruments at the operative site.

Internal impingement of instrumentation was less of a problem in the human cadaveric model, especially with the use of the 30° endoscope, but binding of the external bases and instrument arm mounts still occurred. This was somewhat minimized by using the Point Setter arm instead of the da Vinci camera arm to hold the camera.

Proposed solutions. Although we were able to successfully complete a variety of endoscopic tasks in the human cadaveric larynx, several modifications to the instrumentation and equipment would be necessary before the da Vinci system will have practical applications in otolaryngologic surgery. We propose increasing and varying the lengths of the instrument arms. This would allow surgeons to stagger the mounts, thus minimizing external binding and interference. External binding could also be reduced by slightly angulating the instrument arms (figure 3). Such a modification would be most useful during surgery in the lateral aspects of the pharynx and larynx. Currently, the da Vinci computer recognizes the precise orientation of each instrument. Orientation would be maintained if the angulation were to be changed approximately 10° to 15°—or even more if necessary. A change in angulation

Discussion
For endolaryngeal procedures, the da Vinci system has the potential to allow for adequate access and precise control in the narrow confines of the pharynx and larynx. The EndoWrists allow for seven degrees of movement, compared with the three or four degrees available during most other traditional endoscopic laryngeal procedures. This freedom of movement, combined with the three-dimensional viewing of the operative field and the motion scaling, has the potential to provide precise control and accuracy during all instrument movements.

Technical limitations. There were several apparent

Figure 2. The setup of the da Vinci system for endolaryngeal surgery in our porcine model required that all three robotic arms be placed in close proximity at the head of the operating table. With this type of setup, the robot is operating at the extreme limits of its motion.
would allow surgeons to position the instrument heads away from each other.

Good otolaryngologic endoscopy relies on surgeons receiving clear, bright images from relatively small-diameter endoscopes. The da Vinci system provides a three-dimensional image by routing an image from two separate 4-mm scopes contained within the 12-mm scope. Each image is processed independently and routed to a dedicated cathode-ray-tube monitor in the surgeon’s console. In effect, the right eye sees the image from the right endoscope and the left eye sees the image from the left endoscope. In order to set this instrumentation in the nose or trachea, the endoscope must be made smaller. However, the problem with reducing the size of current rigid scopes is that the size of each image would be reduced, as well. This would severely affect the depth of field. Essentially, a 4- or 5-mm three-dimensional scope would require two endoscopes no larger than 2 mm to route an independent image to the surgeon’s console. Additionally, the endoscope would have to be very near the operating surface in order to obtain a clear image. These modifications, however, would limit the surgeon’s ability to safely visualize incoming instruments or the remainder of the surgical field. One possible solution would be to add a wide-angle filter to the lens, but this would distort the incoming image from the edge of the scope.

In an effort to improve the optics of endoscopes, leading medical optics companies such as Olympus have already developed digital-camera endoscopes equipped with a camera chip or a charge-coupled device (CCD) at the tips of the instruments. These nonfiberoptic endoscopes are used widely in various disciplines, most notably in gastroenterology and pulmonology, and they deliver brilliant magnified images. CCD chips in flexible endoscopes are now available for use in flexible nasopharyngoscopes. These CCD chips are smaller than 2 mm in diameter. One way to reduce the size of the (12 mm) da Vinci endoscope while maintaining sufficient optics and stereovision would be to place these micro-CCDs at the tip of the endoscope. Additionally, a hybrid endoscope outfitted with a rigid proximal shaft and a flexible distal tip would be perfect for use in the lateral recesses of the lateral skull base or around the delicate structures of the skull base. A hybrid scope would provide surgeons with the obvious advantage of being able to work with a rigid scope while enjoying the benefit of the “panoramic” view provided by a flexible scope. Certainly, owing to CCD technology, the development of smaller and more functional scopes for use in clinical practice is just over the horizon. These novel developments in optics might obviate the need for 30°, 45°, and 70° rigid scopes.

Like the da Vinci system, the Zeus Robotic Surgical System (Computer Motion; Goleta, Calif., no longer commercially available) is equipped with three interactive robotic arms. Unlike the da Vinci system, the Zeus system is outfitted with 5-mm instruments and a 10-mm three-dimensional laparoscope. However, the Zeus instruments have nonarticulating tips and provide only five degrees of freedom. Additionally, Nio et al. reported other limitations of the Zeus instrumentation, and they proposed that improvements in size, purpose, and tactile feedback would facilitate robot-assisted endoscopic surgery. Nonetheless, the Zeus system still represented an improvement over traditional laparoscopic instrumentation, and many successful procedures have been performed with it, including the first transcontinental robot-assisted laparoscopic cholecystectomy.

Future applications. Despite the various technical problems we encountered during the setup and operation of the da Vinci system, we were able to successfully complete a variety of endolaryngeal surgical tasks in both the porcine and human cadaveric models. We believe that the development of smaller instrumentation and further advances and modifications in device technology will facilitate the incorporation of surgical robotics into otolaryngology. Such advances might revolutionize the way we perform certain surgical procedures in the head and neck and might elevate minimally invasive endoscopic surgery to a higher level. For instance, endolaryngeal and endotracheal procedures represent exciting opportunities for future innovative endoscopic and robot-assisted surgery. With continued refinement of instrumentation for use in otolaryngology, we envision placing laser fibers on the tips of EndoWrist instruments. Surgeons would then have the ability to perform, for example, a free-form resection of a tumor on the tracheal wall with dexterity and precision (figure 4). Surgeons could also perform endolaryngeal/tracheal reconstruction with applicable EndoWrist instruments. We also envision the potential use of surgical robotics in several other sites: the cervical esophagus (e.g., for endoscopic Zenker’s diverticulectomy and diverticulotomy), the neck (e.g., for endoscopic and robot-assisted dissection, thyroidectomy, and parathyroidectomy), the lateral skull base via minimally invasive entry ports (e.g., for paraganglioma resection and V2 and V3 schwannoma excision), the anterior skull base (e.g., for pituitary surgery and chordoma excision), and the temporal bone (e.g., for mastoidectomy, stapes surgery, cerebellopontine angle tumor resection, and other otologic procedures). Other potential applications may also exist in rhinosurgery, sinus...
surgery, and microvascular reconstruction of defects following head and neck cancer resections.

Obviously, each of these applications requires its own instrumentation, which would require that comparable surgical robotic instrumentation be developed, as well. For example, robotic microdebriders might be helpful for removing endolaryngeal papillomas and endonasal polyps and tumors. Computer-guided EndoWrist drills and microdebriders would allow otologic and skull base surgeons to drill in the intricate recesses of the skull base with pinpoint precision and without hand tremor. Microinstrumentation driven by microdrivers could be used to resect large acoustic schwannomas in the cerebellopontine angle.

In conclusion, the introduction of the da Vinci Surgical System has improved endoscopic procedures in the fields of cardiothoracic surgery, general surgery, gynecology, and urology. We believe surgical robotics also has a place in otolaryngology and that the borders of endoscopic surgery in the head and neck can be expanded. To date, we have already performed 4 robot-assisted total thyroidectomies in humans, as well as an excision of a vallecular cyst. Conceivably, most thyroidectomies could be performed via minimally invasive robot-assisted surgery. Intuitive Surgical, the manufacturer of the da Vinci system, is now developing smaller instruments to overcome some of the system’s current limitations in otolaryngology and other surgical disciplines. The company is also designing a fourth arm for the da Vinci system. When these improvements are realized, future investigations are warranted to exploit the full potential of surgical robotics in otolaryngology.

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References

Figure 4. Artist’s rendition illustrates how a laser fiber placed through the EndoWrist can be helpful in performing a free-form laser resection of a subglottic tumor in an adult.