Past, Present, and Future of Robotic Surgery

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KEYWORDS

• Robotic surgery • Transoral robotic surgery • TORS • History of robotic surgery

KEY POINTS

- Robotic-assisted surgery is the latest form of minimally invasive surgery, building on microsurgical, laparoscopic, and endoscopic techniques.
- Transoral robotic surgery (TORS) takes advantage of the natural oral orifice and allows for en bloc resection of oropharyngeal, hypopharyngeal, and laryngeal tumors.
- Although the cost-effectiveness of robot-assisted surgery is an evolving point of discussion, robotic systems have successfully expanded into the US health care system.
- Introduction of new robotic systems could decrease costs, facilitate wider adoption, and accelerate technological innovation.

INTRODUCTION

The current concept of robotic surgery involves the performance of surgical procedures by using small wristed instruments attached to a robotic arm. The surgeon controls the system obtaining high-definition magnification while taking advantage of the robotic arm's capabilities for precision and miniaturization. Their introduction to medical fields started 30 years ago and now represents one of the fastest areas of growth in the surgical field. Transoral robotic surgery (TORS) has become an effective and safe tool for head and neck surgeons.

PAST

Early Conceptions of Robots

Robots, by definition,[1] are mechanical contraptions able to carry out complex actions automatically. A machine performing a function automatically was firstly described in the myth of Hephaestus, a Greek god that built Talos, a giant made of bronze, to defend the island of Crete.[2] Evidence of human-built machines is found in relics traced as far back as 1500 BC in Egypt, in the form of human figurines striking bells inside water-powered clocks. Nonetheless, the concept of robots as subservient of humanity

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Otolaryngol Clin N Am 53 (2020) 935–941
https://doi.org/10.1016/j.otc.2020.07.005 oto.theclinics.com
0030-6665/20/

has always been ingrained to its name. The word "robot" derives from robota, a Czech word for serf or forced labor. It was coined in 1921, in a Czech play by Čapek,[3] centered on a factory that manufactured artificial, human-shaped workers, to do unwanted labor.

In 1495, under the patronage of the Duke of Milan, Leonardo da Vinci built a mechanical knight (Leonardo's Automa Cavaliere) able to perform humanoid movements, such as sitting and lifting his visor. It was believed to be human-powered and controlled through a crank, linked to a system of pulleys and internal gears.[4] Thus, not exactly a robot, but one impressive prototype design for the many automata later created to entertain the higher classes and royalty, during almost half a millennium. Currently, popular culture influences the collective conception of modern robots, from undisputedly mechanical models, such as C-3PO in the Star Wars movies, or life-like cyborgs from Blade Runner.

Early Robotic Systems

In 1949, Raymond Goerz patented the "master-slave manipulator," an articulated arm intended to safely manipulate radioactive materials from a distance. Goerz's work gave rise to telerobotics, which involves teleoperation (the control of any machine at a distance) and telepresence (capability of remotely exerting effects).[5] Soon afterward, Unimation, the world's first robotic company, created the Unimate, a reprogrammable hydraulic robotic arm that was able to repeatedly perform dangerous transfer tasks.[4] It was the first mass-produced robotic arm for factory automation, and in 1961 it was installed at a General Motors assembly line.[6]

Early Surgical Robotic Systems

The 1980s brought the rise of minimally invasive surgery and its war-horse, the laparoscopic technique, changing the landscape of operating rooms worldwide. But surgery in these ever-decreasing spaces was accompanied by newly discovered limitations to maneuverability and accuracy. These conditions were perfect for the introduction of robots into the nascent field of robotic surgery. In reality, this term is becoming a misnomer, and robot-assisted surgery is a more accurate term, because most systems are not autonomous, but almost completely dependent on an operator.

The early medical robots were specialty-oriented and favored a shared autonomy between surgeon and machine. In 1985, the Unimation Programmable Universal Manipulation Arm (PUMA) 200 used computed tomography (CT) scans to define the trajectory of a brain needle biopsy, in the first documented robot-assisted surgical procedure,[7] with the help of a 6° of freedom manipulator (human wrist has 3° of freedom). Soon after, the PUMA 560 was used to assist with transurethral resection of the prostate.[8] Later in 1989, the Imperial of College in London developed the Pro-Bot, a PUMA robot with a liquidizer blade and aspirator.[9] By preprograming it with transrectal scans, it could automatically perform a transurethral resection of the prostate, within the enclosed prostate's space. Although never commercialized, it was the first truly automatic robot used in medicine.[10] The RoboDoc (a collaboration of University of California, Davis and IBM) was able to automatically perform precise computer-guided femur drilling during hip surgeries, and it was successfully commercialized in Europe and Asia since 1994, gaining Food and Drug Administration (FDA) approval in 2008.[11]

These accomplishments garnered the attention of US government agencies, which were interested in achieving remote surgery capabilities, potentially for astronauts in space and wounded soldiers on the battlefield. A National Aeronautics and Space Administration scientist, Scott Fisher, and Joe Rosen, a plastic surgeon from Stanford

University, collaborated with Phil Green, of the Stanford Research Institute (now SRI International, Menlo Park, CA) and used National Institutes of Health funding to build a new robotic arm.[12]

Computer Motion, Inc (Goleta, CA), created Automated Endoscopic System for Optimal Positioning (AESOP), the first robotic surgery system approved by the FDA, in 1994. It consisted of a voice-controlled robotic arm capable of moving an endoscope during laparoscopy. Meanwhile, the licensing rights from the SRI system were sold to Fredrick Moll, John Freund, and Robert Younge, forming Intuitive Surgical, Inc (Sunnyvale, CA). They updated their acquisition to "Lenny," an early prototype of the da Vinci, followed by other prototypes "Leonardo," "Mona," and finally, the da Vinci surgical system.[13]

Computer Motion went on to build the ZEUS robotic surgical system using AESOP's technology and focused on cardiovascular and gynecologic procedures. In 2001, the Zeus was used for the famous Lindbergh operation, where surgeons in New York performed a cholecystectomy on a patient in Strasbourg, France. Although the system received FDA approval for limited use in 2001,[14] its production was phased out, along with the AESOP, when the company was bought by Intuitive in 2003.

Multiple other robots have been developed, such as the Neuromate (Integrated Surgical Systems, Sacramento, CA), which received FDA approval in 1999 for stereotactic neurosurgical procedures, or the Steady Hand Robot, developed at Johns Hopkins University (1999), to offer counterforce to the movement of the hand to cancel tremor during retinal surgery.

Advent and Use of the da Vinci System

Although the da Vinci is currently the most commonly used surgical robotic system, it completely lacks autonomy, providentially more akin to Leonardo da Vinci's human-powered automata, than other earlier surgical robots. The original da Vinci robotic system had three arms and was commercialized in Europe since 1998 for coronary surgery, before receiving FDA clearance in 2000 for general surgery procedures.[15] In 2001 it was approved for prostate surgery,[16] followed by clearance for gynecologic, thoracoscopic, and cardiovascular procedures.[17,18]

The system consists of a master console with a magnified ($\times$10), high-definition, three-dimensional view of the surgical field; a video platform/laparoscopic insufflator; and a patient-side cart with movable robotic arms. Each arm holds detachable surgical tips through wristed technology, allowing 6° of freedom (3° of translation, 3° of rotation) and 90° articulation, providing human handlike rotation, with an additional degree of freedom given by the attached tool (cutting, grasping). The surgeon can operate the robotic arms, through scaled, finger-controlled cuffs. The most immediate advantages were the annulment of hand tremor and improved dexterity in minimally invasive accesses while maintaining optimal vision.[19]

In 2003 it was upgraded with a fourth arm, for optimal retraction, suction, and irrigation. In 2006 the da Vinci S HD (second generation) added improved resolution, swifter instruments exchange, fewer cable connections, extended-reach instruments (for multiquadrant access), and interactive multi-image displays (TilePro). In 2009 the da Vinci Si HD added shared-control capacity between dual consoles, for training and collaboration, along with improvements to the user interface, digital OR integration, and video resolution.[20]

In 2014, the da Vinci Xi (fourth generation) brought thinner, longer arms; the capability of using fluorescent imaging (Firefly); and a changed setup to an overhead arrangement. It can be connected to a special operating table, for integrated table motion, which allows the repositioning of the patient without having to undock the robotic arms during multiquadrant surgery.[21] A lower-cost version, the X, was released in 2017, with the upgrades of the Xi (also voice and laser guidance, and a lightweight endoscope) but with reduced versatility, because it is installed in a side cart.[22]

PRESENT

Current State of Robot-Assisted Surgery

The presence of robots in the hospital system has grown impressively, despite steep entry costs. Nowadays, the popular perception is favorable to the use of surgical robots and the hospitals that have them.[23,24] Correspondingly, an institution looking to promote minimally invasive surgery capability needs to have a robot. The market is currently dominated by the da Vinci, and approximately 5000 active systems perform more than a million robotic surgeries each year.[25] Robot-assisted surgery is currently used within the fields of breast surgery, obstetrics and gynecology, endocrine surgery, hepatobiliary, thoracic, colorectal and general surgery, urology, and otolaryngology. The latter is mostly through TORS.

TORS takes advantage of the natural oral orifice, permitting en bloc resection of pharyngeal and laryngeal tumors.[26,27] The da Vinci Si was FDA approved in 2009 for malignant and nonmalignant diseases of the tongue base, oropharynx, and supraglottic larynx. The fourth arm is not used because of anatomic constraints. In selected patients (stage II to IVa) with oropharyngeal cancer, TORS could be more cost-effective than nonsurgical treatment.[28]

In 2016 the FDA approved the da Vinci Xi for general laparoscopic surgical, urologic, and gynecologic procedures, but not for head and neck procedures. Thus, most of the literature for TORS is based on the Si Model. Still, the off-label use of the Xi model in TORS has been reported in the United States.[29]

The use of the robotic systems has also been reported in the parapharyngeal space, the nasopharynx, clivus, and upper cervical vertebrae, sometimes aided by open approaches to gain the necessary exposure.[30] Additional evolving applications of robotic technology in otolaryngology include use for neck procedures (eg, neck dissection), endocrine (ie, thyroid/parathyroid) surgery, salivary gland surgery, sleep surgery, sinus and anterior skull base surgery, otology/neurotology, and pediatric surgeries.

Other Robotic Models in Use

In 2013 Stryker (Kalamazoo, MI) became the first major surgical instrument company to get involved in robotics through its acquisition of Mako Surgical, and its Robotic-arm Interactive Orthopedic System, approved for knee and hip replacements (MAKOplasty). Through preoperative CT scan modeling, an area of safe surgery is delineated, and haptic boundaries limit the robotic arm.[31]

A novel robotic technology that is observed in current operative rooms is robot-assisted flexible endoscopy. The Monarch (Auris Health Inc, Redwood City, CA) was approved by the FDA for diagnostic and therapeutic bronchoscopy procedures in 2018. Through flexible endoscopes, radial endobronchial ultrasound and a videogame-like controller, needle biopsies are taken under direct vision. Recently, Johnson & Johnson (New Brunswick, NJ) acquired Auris Health, led by Fred Moll, and more than 1000 procedures have been performed in multiple US hospitals.[32] In 2019, Intuitive Surgical obtained FDA approval for the Ion endoluminal system. A robotic-assisted lung biopsy platform includes a thin, fully maneuverable robotic catheter of 3.5 mm with a 2-mm working channel. The Ion allows direct vision while able to integrate other imaging technologies, such as fluoroscopy, radial endobronchial ultrasound, and cone-beam CT. The future aim is to expand robot-assisted flexible endoscopy to gastrointestinal[33] and urologic procedures.[34]

Single-port robotic systems include the use of a single robotic arm containing an endoscope and instruments. Currently, single-port systems are available through Intuitive (Single Port) and Medrobotics (Flex Robotic System). The surgical system by Titan Medical is currently in development and features a single-port robotic system, with multiarticulated instruments.

There have also been efforts to unify the operative room system with robotic technology. This includes the Renaissance Surgical System, a bone-mounted guidance system for accurate spinal surgery, and the Mazor X, a robotic arm able to hold surgical wires or be accommodated to Medtronic (Minneapolis, MN) StealthStation software. It is commercialized as a fully integrated experience of preoperative planning, live intraoperative three-dimensional imaging, and powered surgical tools.[35]

FUTURE

The continuous growth of robot-assisted surgery depends on the concept that they will become essential to operative environments in the time to come, in a way not dissimilar to laparoscopic and endoscopic techniques. Because the da Vinci is the most commercially successful model, it also sets the standard for improvement of the current weaknesses of robot-assisted surgery. Its large, rigid arms hinder the ability to obtain an adequate site of exposure. Its cutting tools are limited, and its set-up is time-consuming. A well-trained team is required, to compensate for the time loss of placing the sterile draping, arranging the carts, and attaching and positioning the instruments.

The da Vinci performs well in anatomically enclosed spaces (prostate, uterus), but its lack of haptic feedback results in a well-known risk of tissue-manipulation damage. The open and dynamic anatomic barriers of the head and neck could be more forgiving. Nevertheless, the system and its rigid instruments could benefit from enhanced sensorial input and instruments adapted to the surgery type, to refine surgical capabilities and exposure.

However, the most important barrier to wider adoption is the financial burden, not only of the machine but also its maintenance and consumables. Some of the earliest Intuitive patents started expiring in 2016, and the increasing competition should contribute to decreasing costs.

Potential Improvements to Robotic Technology

Certain developments are needed, such as an improved, validated curriculum, and better delineation of indications, especially in oncologic scenarios. The system could immensely benefit from additional tools (ie, ultrasound guidance) and smaller surgical tips with upgraded abilities, such as bone drilling capacity. The latter would allow bringing robotic surgery to the skull base, cervical spine, and beyond.

Multiple efforts have focused on creating a more streamlined experience in the operative room, by integrating surgical robotics to other new technologies. Image guidance and navigation could become the next frontier for advancements, by overlaying key clinical imaging (augmented or virtual reality) on the surgical field and incorporating machine learning.

Other projections are the expansion of uses of telesurgery, either for telesurgery in rural remote areas or within the confines of a single hospital. This could potentially allow performing multiple procedures in parallel, increasing efficiency.

Nano-robots are another area of potential future applications. These small robots are projected to be able to travel the bloodstream, locally delivering medication and even performing cellular-level surgery.

SUMMARY

Robotic-assisted surgery embodies the latest in technological advancement, applied to the operating management of a patient. Its extension to otolaryngology seems only natural because natural orifices are exploited for access while minimizing disruption to normal structures and optimizing function. Its recent growth and the imminent addition of novel technology could signal the advent of a new era in surgery.

DISCLOSURE

The authors have nothing to disclose.

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