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30 Years of Robotic Surgery

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Abstract The idea of reproducing himself with the use of a mechanical robot structure has been in man's imagination in the last 3000 years. However, the use of robots in medicine has only 30 years of history. The application of robots in surgery originates from the need of modern man to achieve two goals: the telepresence and the performance of repetitive and accurate tasks. The first "robot surgeon" used on a human patient was the PUMA 200 in 1985. In the 1990s, scientists developed the concept of "master–slave" robot, which consisted of a robot with remote manipulators controlled by a surgeon at a surgical workstation. Despite the lack of force and tactile feedback, technical advantages of robotic surgery, such as 3D vision, stable and magnified image, EndoWrist instruments, physiologic tremor filtering, and motion scaling, have been considered fundamental to overcome many of the limitations of the laparoscopic surgery. Since the approval of the da Vinci® robot by international agencies, American, European, and Asian surgeons have proved its factibility and safety for the performance of many different robot-assisted surgeries. Comparative studies of robotic and laparoscopic surgical procedures in general surgery have shown similar results with regard to perioperative, oncological, and functional outcomes. However, higher costs and lack of haptic feedback represent the major limitations of current robotic technology to become the standard technique of minimally invasive surgery worldwide. Therefore, the future of robotic surgery involves cost reduction, development of new platforms and technologies, creation and validation of curriculum and virtual simulators, and conduction of randomized clinical trials to determine the best applications of robotics.

Introduction

The idea of reproducing himself with the use of a mechanical robot structure has been in man's imagination in the last 3000 years. However, the use of robots in medicine has only 30 years of history. The purpose of this article was to describe the evolution, current status, and future perspectives of robotic surgery.

From literature to the real world

The application of robots in surgery originates from the need of modern man to achieve two goals: the telepresence and the performance of repetitive and accurate tasks. The first goal was achieved in 1951. Raymond Goertz, while working for the Atomic Energy Commission (USA), designed the first teleoperated mechanic arm to handle hazardous radioactive material [1, 2]. The second was achieved in 1961, when George Devol and Joseph Engelberger developed the first industrial robot called Unimate for General Motors. These successful experiments were determining factors for the introduction of Robotics in all other industrial areas around the world [3, 4]. Although it was used in the literature by Karel Čapek and Isaac Asimov

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Fig. 1 Programmable universal machine for assembly (PUMA) 200

in the 1920s and 1940s, respectively, the first definition of the word "robot" was published by the Robots Institute of America in 1979: "a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks" [5–7].

The concept of pre-programmable "robot surgeon"

The first "robot surgeon" used on a human patient was the programmable universal machine for assembly 200 (PUMA), developed by Victor Scheinman in 1978, and employed by Kwoh in 1985 to perform neurosurgical biopsies (Fig. 1) [8, 9]. The accuracy and successful results obtained with PUMA led to its application in urology surgeries at the Imperial College in London, in 1988 [10]. This robot was substituted later by the surgeon-assistant robot for prostatectomy (SARP) and the prostate robot (PROBOT), both used in prostate surgery, and UROBOT commonly used in urological procedures [8, 11]. These robots had to be preprogrammed based on the fixed anatomic landmarks of each patient and could not be employed in dynamic surgical targets (e.g., gastrointestinal surgery) [8].

The concept of robotic telesurgery

The announcement of American former President George H. W. Bush, regarding the intention to put man on Mars, led researchers at NASA's Ames Research Center to develop research projects to address the necessity of performing long-distance surgeries in astronauts. With that in mind, investigators Michael McGreevey, Stephen Ellis, and Scott Fischer developed a stereoscopic display unit with 3D vision called head-mounted display (HMD) to give the astronauts access to real-time data [12]. HMD combined with data gloves, created by Jaron Lanier, allowed the user to interact with the virtual world [8]. At the same time, Philip Green, at the Stanford Research Institute (SRI), and the military surgeon Richard Satava developed an operating system for instrument telemanipulation [13]. The computer scientist, Scott Fischer, and the plastic surgeon, Joseph Rosen, produced the fundamentals of telepresence surgery to perform surgeries in space through the combined use of HMD, data glove, and SRI telemanipulator [8]. Unfortunately, the pioneer projects of telepresence surgery were not technically feasible [14]. The HMD was replaced with monitors and the data gloves with handles for controllers at the surgeon's console [8]. In 1989, Jacques Perissat presented the laparoscopic cholecystectomy technique at the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) meeting in Atlanta. This novelty called the attention of a group led by Richard Satava for developing a robotic system that could be applied to laparoscopic surgery [15].

The interest of the United States Department of Defense to provide medical assistance to wounded soldiers in the battlefield resulted in a Defense Advanced Research Projects Agency (DARPA) grant for the development of a robotic system. This project resulted in a prototype mounted into an armored vehicle (the Bradley 557A) that could "virtually" take the surgeon to the front lines [14]. The first remote surgical procedure, an ex vivo intestinal anastomosis, was performed by Dr. Jon Bowersox [16].

The concept of master–slave robot

In the 1990s, scientists developed the first "master–slave system," which consisted of a robot with remote manipulators controlled by a surgeon at a surgical workstation [8].

Automated endoscopic system for optimal positioning (AESOP)

In 1993, Yulin Wang founded the Computer Motion Inc. (Goleta, CA, USA) and developed the Automated Endoscopic System for Optimal Positioning (Fig. 2). In the

Fig. 2 Automated endoscopic system for optimal positioning (AESOP)

following year, the Food and Drug Administration (FDA) approved AESOP as an endoscopic camera manipulator controlled by the surgeon's voice commands, eliminating thus the need of an assistant to perform this task [17–19]. There are some literature reports that describe the application of AESOP in laparoscopic cholecystectomy, hernioplasty, fundoplication, and colectomy [20].

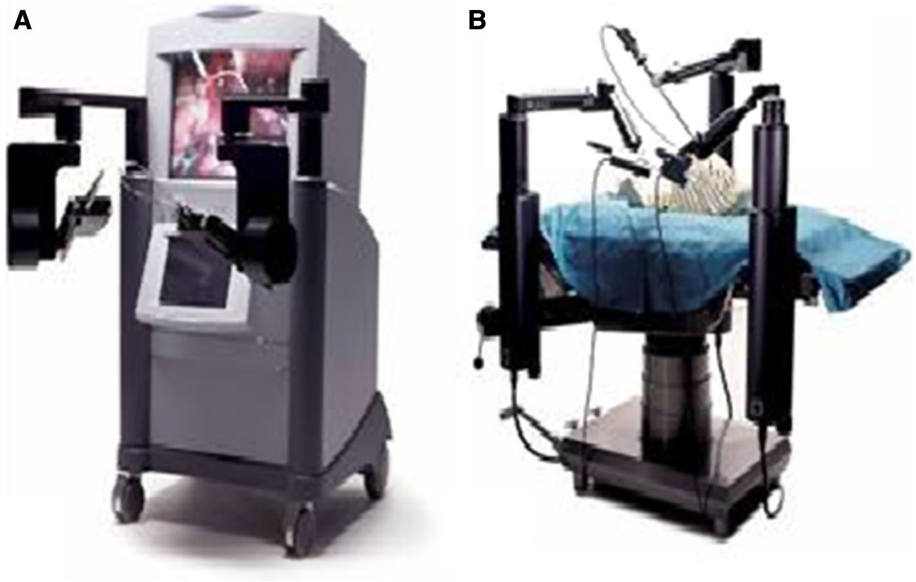
Zeus

Not satisfied with the concept of telemanipulation of video camera, Wang obtained funding from DARPA to develop a robot capable of reproducing the movements of the arms of the surgeon. As a result, the Zeus system was created with arms and surgical instruments controlled by the surgeon (Fig. 3) [15]. The ZEUS robotic surgical system was first used in a fallopian tube anastomosis at the Cleveland Clinic, Ohio, USA, in July 1998 [21]. There are reports in the literature describing the use of ZEUS in digestive (cholecystectomy, appendicectomy, bariatric, hernioplasty, gastrectomy, fundoplication, splenectomy, and colectomy), urologic, gynecologic, and heart surgeries [22]. On September 3, 2001, ZEUS was used for the first-ever transatlantic telesurgery. A laparoscopic cholecystectomy was performed in Strasbourg, while the surgeon, Dr. Jacques Marescaux, was in New York [23]. In 2003, following a long legal battle, the Computer Motion, Inc., merged with Intuitive Surgical Inc. and discontinued the development of the ZEUS [24].

The current status of robotic surgery

The da Vinci® robot is a master–slave device developed by Intuitive Surgical Inc. It is currently the most widespread robotic surgical system, with more than 3400 units sold worldwide and thousands of peer-reviewed publications. The first robotic-assisted cholecystectomy was performed by Jacques Himpens and Guy Cardiere, in Brussels, Belgium, in 1997 [25]. A prototype "Mona" was employed. Following this successful surgical procedure, myocardial

Fig. 3 ZEUS robotic surgical system. **a** surgeon console and **b** robotic arms



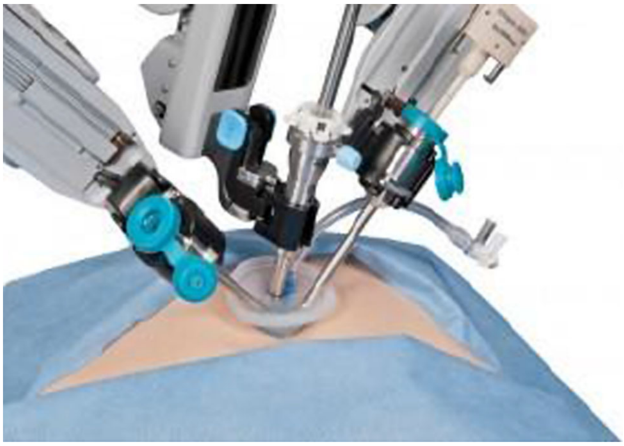


Fig. 4 Da Vinci® Single-Site® system

revascularization surgeries were performed at the University of Leipzig in Germany, in 1998 [26]. Although the cardiac surgery was the main focus of the industry upon the development of the da Vinci®, the results obtained in this area were not as satisfactory as those achieved in general surgery [27]. However, 300 robotic surgeries had to be performed in Europe, mainly cholecystectomy and fundoplication to prove the safety of this new technology. The use of the da Vinci® device in abdominal surgeries in humans in the United States received the FDA approval on July 17, 2000 [28]. However, only after the first robotic radical prostatectomy performed in the USA, in 2000, that da Vinci® became commonly employed in urologic and gynecological surgeries, including prostatectomy for cancer and hysterectomy for benign diseases [29–31].

The da Vinci® robotic system overcomes many of the limitations of the laparoscopic surgery, basically the 2D vision of the operating field, fulcrum effect, and non-articulated instrument arms [32]. Technical improvements, such as highly magnified 3D vision, precisely controlled EndoWrist instruments with seven degrees of freedom, and the preservation of natural eye-hand-instrument alignment, made the robotic platform more attractive for surgeons to use da Vinci® in a wide range of surgical procedures during the first decade of the millennium. Some other features, including stable image of the operative field, magnification of the image up to 10×, physiologic tremor filtering, motion scaling of up to 5:1, and better ergonomics, have also been mentioned in scientific articles and announced by the industry as advantages of da Vinci® [26, 33].

Along with the successive generations of da Vinci® models, some new adjunctive tools and accessories were developed such as

- Da Vinci® Single-site (Fig. 4): this system has eliminated the fulcrum effect and reestablished the instrument triangulation, both considered essential features when performing minimally invasive surgical procedures [34].
- FireFly system: combines a special video camera and a fluorescent dye (indocyanine green), which is injected

Table 1 Timeline of the da Vinci® surgical system in general surgery

Year	Author	Surgery
1997	Cadiére [25]	Cholecystectomy
1998	Cadiére [39]	Adjustable gastric band
1999	Cadiére [40]	Nissen fundoplication
2000	Horgan [41]	Roux-en-Y gastric bypass
	Giulianotti [42]	Total gastrectomy in malignant disease
	Hashizume [43]	Colectomy in malignant disease
	Hashizume [43]	Splenectomy
	Hashizume [43]	Unilateral and bilateral inguinal hernia repair
2001	Weber [44]	Colectomy in benign disease
	Horgan [41]	Adrenalectomy
	Giulianotti [42]	Liver resection
	Giulianotti [42]	Distal pancreatectomy and duodenopancreatectomy
	Melvin [45]	Heller's esophagomyotomy
	Melvin [45]	Transthoracic esophagomyotomy in malignant disease
2002	Ballantyne [46]	Ventral and incisional hernioplasty
2003	Horgan [47]	Transhiatal esophagectomy in malignant disease
	Giulianotti [42]	Anterior resection of the rectum
2007	Kang [49]	Thyroidectomy in malignant disease

Table 2 Levels of evidence and best indications for robot-assisted general surgery [51]

Surgery	BLOE	Main benefit (LOE)
Multi-site cholecystectomy	3B	Robotic surgery training (3B)
Single-site cholecystectomy	3B	To overcome technical difficulties of the SSLC (4)
Bariatric surgery	3A	↓ Learning curve of gastric bypass (3A)
Nissen fundoplication	1B	Repair of recurrent GERD or hiatal hernia (5)
Gastrectomy in cancer	2A	Lymphadenectomy and gastrointestinal reconstruction (4)
Splenectomy	3B	To facilitate the approach to splenic hilum (3B)
Inguinal hernia repair	4	–
Colectomy in cancer	1B	Intracorporeal anastomosis (4) / ↓ conversion (2A)
Adrenalectomy	3B	Voluminous tumor of right adrenal gland (5)
Liver resections	3A	↑ Minimally invasive hepatectomy rate (3B)
Distal pancreatectomy	3B	↑ Splenic preservation rate (3B)
Duodenopancreatectomy	3B	↓ Perioperative bleeding (3B)
Heller's esophagomyotomy	2B	↓ Esophageal mucosa perforation rate (2B)
Incisional hernioplasty	4	–
Esophagectomy in cancer	2B	↓ Recurrent laryngeal nerve palsy rate (3B)
Proctectomy in cancer	2A	Preservation of genitourinary function (3A)
Thyroidectomy in cancer	3B	Better esthetic outcome (3B)

BLOE best level of evidence, *LOE* level of evidence, *SSLC* single-site laparoscopic surgery, *GERD* gastroesophageal reflux disease

intravenously during the surgery. This resource gives a detailed picture of the vessels (e.g., partial nephrectomy) and the biliary tract (e.g., intraoperative cholangiography) [35].

- Double console: mainly used for training novice surgeons, possibly reducing the learning curve in robotic surgeries [26, 36].
- Til Pro system: allows a simultaneous visualization of two image sources in the monitor (e.g., computerized tomography and intraoperative echography). It has been employed for intraoperative studies on vascular anatomy (e.g., partial nephrectomy) [37].
- Natural orifices translumenal robotic surgery: one of the most promising applications of this technique has been the robotic transanal minimally invasive surgery (RATS) [38].

Robotics in general surgery

Since the FDA approval of the da Vinci® 15 years ago, American, European, and Asian authors have described techniques for the performance of many different robot-assisted surgeries, proving not only its factibility but also its safety (Table 1) [25, 39–48].

The technical advantages offered by the da Vinci® robot are not necessarily translated into better clinical outcomes. Many comparative studies, mostly with low level of evidence (Table 2), with patients submitted to many different robotic and laparoscopic surgical procedures in general surgery, have shown similar results with regard to the adequacy of oncologic resection (surgical margins and lymph node sampling), functional results (quality of life), and postoperative recovery (time of hospitalization and rehospitalization, reoperation, perioperative morbidity and mortality rates). Some well-designed studies, however, have reported the benefits of robotic resection of the rectum in terms of better genitourinary function preservation and possibly lower conversion rate, particularly in male, obese, and low rectal tumors [49, 50]. Until now, the surgical time and hospital costs have been invariably unfavorable to robotics in cost-effectiveness studies published to date. Therefore, the tendency is to indicate the robotic surgery in situations with major benefits (Table 2) [51, 52].

Robotic surgery simulation

In 2006, Mimic Technologies Inc. (Seattle, WA, USA) unveiled the first robotic surgery simulator, the MIMIC® da Vinci virtual reality trainer, for the da Vinci® System [53, 54]. The following year, Mimic and Intuitive Surgical Inc., introduced the da Vinci® Skills Simulator, a device similar to a backpack that was attached to the back of the Vinci® Si or Xi console (Fig. 5) [53]. Finally in 2008, the simulated surgical systems released the robotic surgical simulator, very similar to the da Vinci® console [53].

Fig. 5 Da Vinci® Skills Simulator integrated with the da Vinci Si® surgeon console

The future of robotic surgery procedures

The future of robotic surgery involves basically five aspects:

New platforms and robotic surgery technologies

New robotic surgical systems with unprecedented technological resources are currently being developed and tested: (1) Surgeon's Operating Force-feedback Interface Eindhoven (SOFIE, Eindhoven University of Technology, Holland) and DLR-MIRO (Institute for Robotics and Mechatronics, Germany), both with haptic feedback [55, 56]; (2) TELELAP ALF-X® (SOFAR S.p.A, Italy), with an eye tracking system for handling the telecamera [57]; and (3) Titan's Single Port Orifice Robotic Technology (SPORT) surgical system (Titan Medical Inc., Canada), developed for robotic single-site surgery [58].

In vivo miniature robots

Miniature robots were created to be introduced through small incisions for teleoperation in inner cavities. These robots are currently being developed and tested in animal models [59].

Creation and validation of curriculum and virtual robotics simulators

The rapid adoption of the da Vinci® surgery minimally invasive therapeutic devices in the 2000s led to the development of virtual reality simulators and specific training curriculum, such as the fundamental skills of robotic surgery as well as others currently in process of editing by the American Society of Colon and Rectal Surgeons and European Academy of Robotic Colorectal Surgery [60, 61].

Cost reduction

The breaking of patent of the da Vinci® is expected in the coming years and the release of new robotic platforms will be the determining factors to reduce costs for the purchase and maintenance of robots, making the technology accessible to a larger number of hospitals [62].

Scientific research of clinical applications of robotic surgery

Randomized clinical trials should be performed to determine whether the high costs and the longer operative time of robotic surgeries are justified by better oncological outcomes and functional results of this technology [63, 64].

Conclusion

The three decades that have passed since the first robot-assisted surgery performed in humans were of paramount importance for the development of the concept of master–slave robotic platform. The numerous technical advantages and the significant clinical benefits offered by robotic surgery are, however, still being argued due to the extremely high cost of this system. The consolidation of robotics in the therapeutic arsenal of general surgery will necessarily depend on the publication of randomized clinical trials to prove its real clinical benefits, the cost reduction through the break of the patent of the company that currently dominates the market, and the release of new robotic platforms and technologies.

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