The Evolution of Minimally Invasive Robotic Surgery in the Last 20 Years

1

Michele De Rosa, Walter Bugiantella, Federica Arteritano, Lorenzo Mariani, Fabio Ermili, and Graziano Ceccarelli

1.1 Introduction

About a century and a half after the introduction of the first endoscope prototypes [1], the first laparoscopic appendectomy in 1980 [2] marked the beginning of the era of modern minimally invasive surgery [3].

After the full integration of laparoscopy into the surgical armamentarium, supported by several compelling results, at the dawn of the new millennium the robotic approach represented the next step in this revolutionary process, specifically conceived to address most of the technical limitations of conventional laparoscopy, with enhanced visualization, superior dexterity and precision.

Although its application in surgery dates back to 35 years ago, the last two decades have witnessed how this system has slowly, but constantly, gained the approval of the surgical community, becoming a new standard of care. From the first robotic systems to the new emerging platforms, a brief but intense technological development has been observed and implementation of virtual reality, computer assistance and artificial intelligence will introduce a significantly different method of operating (Table 1.1).

M. De Rosa (✉) · W. Bugiantella · F. Arteritano · L. Mariani · F. Ermili · G. Ceccarelli
General and Robotic Surgery Unit, San Giovanni Battista Hospital, Foligno (Perugia), Italy
e-mail: michele.derosa@nhs.net; dr.bugiantella@gmail.com; federica.arteritano@uslumbria2.it; lorenzo.mariani@uslumbria2.it; fabio.ermili@uslumbria2.it; g.cecca2003@libero.it

G. Ceccarelli, A. Coratti (eds.), *Robotic Surgery of Colon and Rectum*, Updates in Surgery, https://doi.org/10.1007/978-3-031-33020-9_1

Table 1.1 A timeline of the modern era of minimally invasive surgery

1983	First laparoscopic appendectomy	Semm [2]
1983	Transanal endoscopic microsurgery	Buess et al. [4]
1985	First laparoscopic cholecystectomy	Mühe [5]
1985	PUMA 560 brain biopsy	Kwoh et al. [6]
1991	First laparoscopic colectomy	Jacobs et al. [7]; Fowler et al. [8]
1991	Probot	Imperial College of London
1992	Robodoc	Integrated Surgical Systems
1994	AESOP 1000	Computer Motion
1995	Intuitive Surgical foundation	
1997	Robotic cholecystectomy – Intuitive Mona	Himpens et al. [9]
1998	ZEUS	Computer Motion
1999	da Vinci first generation	Intuitive Surgical
2001	Lindbergh operation – First telesurgery	Marescaux et al. [10]
2002	First robotic colectomy	Weber et al. [11]
2003	Computer Motion & Intuitive Surgical merge	
2006	da Vinci S	Intuitive Surgical
2009	da Vinci Si	Intuitive Surgical
2014	da Vinci Xi	Intuitive Surgical
2015	Flex Robotic System	Medrobotics Corporation
2017	da Vinci X	Intuitive Surgical
2017	Senhance Robotic System	TransEnterix Surgical
2018	da Vinci SP	Intuitive Surgical

1.2 Background

The Czech word "robota" describes forced labor or activity and appeared almost a century ago in the science-fiction play *R.U.R. Rossumovi univerzální roboti* (R.U.R. Rossum's Universal Robots) by the novelist Karel Čapek. Since then, the term has been used to define a machine-orientated ultraprecise, repetitive, and preprogrammed procedure.

The application of robotics in surgery is relatively recent and is directly derived from military projects aiming to develop a technology to be used in hostile environments where the expert surgeon is away from the patient. The concept of telesurgery or remote surgery entails wireless networking and robotic technology to connect surgeons and patients who are geographically distant, and has become one of the main driving forces behind the development of surgical robots. The "space race" with the launch of the Sputnik and the creation of the NASA (National Aeronautics and Space Administration) were additional factors concurring to the evolution of robotics and telepresence. By 1980 an intense period of discovery and research started with the DARPA (Defense Advanced Research Projects Agency) funding several institutions to expand telepresence surgical systems featuring remote articulating arms and stereoscopic imaging. Although not fully developed, all the tools and systems characterizing the robots we use today originated from those intuitions, which allowed robotic-assisted surgery to make its appearance in the operating room in the mid 1980s [12, 13].

1.3 Robotic Platforms

In 1985, a standard industrial robotic system, the PUMA 560, was used to orient a needle for a computed tomography-guided brain biopsy, providing automatic positioning and greater accuracy compared to a human hand [14]. Shortly afterwards, the same technology was used by Davies to perform a transurethral resection of the prostate (TURP) [15]. The London Imperial College later developed a computer-integrated system for prostatectomy named PROBOT and in 1992 the ROBODOC system (Integrated Surgical Systems, Sacramento, CA, USA) was designed to improve the precision of total hip arthroplasties [16].

In 1994 the AESOP 1000 (Automated Endoscopic System for Optimal Positioning 1000 – Computer Motion, Santa Barbara, CA, USA), a table-mounted robotic arm controlled by the surgeon’s voice commands to manipulate a laparoscopic camera, was approved by the FDA and marketed [14]. In 1998 the Zeus robotic platform (Computer Motion, Santa Barbara, CA, USA) was introduced and the concept of telerobotics was finally realized with the surgeon seated at a console distant from the operating field. The system was equipped with a console, a 3D imaging system and three independent arms, one AESOP arm and two surgical arms with four degrees of freedom, manipulated by two handles. Cardiac surgery was the most relevant field of application, and in 2001 a transatlantic cholecystectomy, the so-called Lindbergh operation, was performed with the surgeon operating in New York while the patient was in Strasbourg, France.

1.4 The da Vinci Era

Years earlier, when the ZEUS system was already in use, Intuitive’s first robotic surgical prototype was developed. This platform presents three main components: a master console where the operating surgeon sits, a vision cart holding a dual light source and dual cameras, and a patient-side moveable cart where the robotic arms are mounted. The master console consists of an image-processing computer generating a true three-dimensional image with depth of field; a stereoscopic viewer port where both eyes are accommodated allowing a binocular visualization with greater focus and comfort; foot pedals to control electric devices, instrument/camera arm clutches and master control handles controlled by the surgeon to drive the servant robotic arms. The instruments are cable-driven and provide seven degrees of freedom and two degrees of axial rotation, imitating the human wrist. Motion scaling and tremor elimination enhance accuracy and precision. The camera arm contains two 5-mm scopes and the image projected onto two screens is truly three-dimensional and is displayed above the hands of the surgeon giving the illusion that the tips of the instruments are an extension of the control grips and the impression of being at the surgical site [17].

Early experiences included a cholecystectomy performed with the second-generation prototype Mona by Himpens operating from Saint-Blasium General

Hospital in Dendermonde, Belgium [9], and a mitral valve replacement by Carpentier [18].

In 2000 the da Vinci robot obtained FDA approval for general laparoscopic procedures and became the first operative surgical robot in the United States.

In 2003, after three years of legal battle, Computer Motion merged with Intuitive Surgical discontinuing the development of the ZEUS system and combining innovations and improvements on the da Vinci platform.

The first da Vinci robot had three arms, of which one for the endoscope, but a four-arm robotic version was approved for clinical use two years later.

The first-generation da Vinci robot featured 3D vision and their patented EndoWrist technology with “7 degrees of freedom” and 90-degree articulation, mimicking the human wrist. Seven years later the da Vinci S was released with 3D high-definition camera vision, a simplified set-up and an interactive touch-screen display.

Several new features became available in 2009, when the da Vinci Si was released, including a dual console for training purposes, Firefly fluorescent imaging, TilePro software showing on screen up to three different images, the surgical field and two other video sources like ultrasound or EKG simultaneously, along with an upgraded 1080i camera.

In 2014, a more advanced and versatile version of the da Vinci, the fourth-generation Xi platform, was released. Access of the robotic arms to all abdominal quadrants without the need for re-docking and moving the operating table while the robotic arms are docked, offer the opportunity to perform multiquadrant single-docking procedures with more ease and consequently decreased operative time. Visualization is improved with a 1080p camera and simplified trocar placement decreases instrument and arm clashing. Furthermore augmented-reality software allows the assessment of intestinal perfusion or real-time 3D anatomical simulation of abdominal structures [19, 20].

The da Vinci X, a smaller version of the Xi, has been available since 2017 and without the table motion technology it is designed for single-quadrant applications.

The game-changing SP da Vinci robotic platform has been recently introduced and approved by the FDA for urological procedures, anticipating what is expected to happen soon for colorectal surgery, where preliminary studies have already demonstrated its feasibility and usefulness mainly in transanal and endoscopic procedures. This is a single-port system, consisting of a 2.5-cm cannula with three fully elbowed EndoWrist instruments and a fully articulating 3D HD endoscope, including a 360-degree boom with 360-degree instrument rotation.

1.5 Robotic Colorectal Surgery Landmarks

The year 2002 marks the publication of the first case series of robotic-assisted colon resections for benign disease [11], as well as the first cases of patients with colon cancer [21].

In 2003, Delaney described the first case of robot-assisted rectopexy and Giulianotti reported six cases of robot-assisted rectal anterior resection for rectal cancer [22, 23], while in 2006 a case series of robotic low anterior resections with total mesorectal excision (TME) for cancer was published, showing no significant differences in perioperative clinical outcomes compared to the conventional laparoscopic approach [24].

Soon thereafter, several groups began publishing data comparing robotic and laparoscopic colorectal surgery [25]. Robotic systems seem to provide major advantages mostly in rectal surgery, where the operation in a narrow and deep space such as the pelvis may benefit from 3D views and accurate manipulations with wristed microinstruments. Therefore, although most of the studies published so far, such as the ROLARR (Robotic vs. Laparoscopic Resection for Rectal Cancer) trial [26], did not demonstrate significant benefits of robotics compared to laparoscopy, a growing number of robotic rectal resections has been reported and is expected to increase further.

1.6 Emerging New Robotic Platforms

Although the da Vinci platform has dominated the world of robotics for more than a decade, the technological advancement in this field of research is constantly progressing, with each day bringing new devices.

The Senhance Surgical System (TransEnterix, Morrisville, NC) entered the market after being cleared by the FDA in October 2017. It consists of a surgeon console unit provided with a HD-3D monitor, requiring special 3D glasses, and two master controllers moving four robotic arms, endowed with non-wristed laparoscopic 5-mm instruments. The system also includes haptic force feedback and an advanced eye-tracking technology which allows the surgeon to control the camera with eye movements [27].

The CMR Versius Surgical Robot (Cambridge Medical Robotics, Cambridge, UK) is a lightweight, modular platform with a surgeon's console and three or four independent robotic units approved in Europe, Australia, India, Brazil and Honk Hong for urology, gynecology, and general surgery [28].

The Flex robotic system (Medrobotics Corp., Raynham, MA, USA) is the first platform provided with a flexible robotic arm, housing at the tip a miniaturized 3D-HD camera flanked by two working channels accommodating flexible dedicated instruments. The system is completed by two main units, the Flex Control Console to move the flexible endoscope through a joystick and the Flex Cart and Base which carries the base and is point of communication between the console and the robotic arm.

Despite being initially conceived for transoral applications, the system received FDA and European Union clearance for transanal applications. Indeed, the special design suitable for endoluminal navigation makes it useful for minimally invasive transanal excisions, but also for more complex operations, as proved by the feasibility study of transanal TME [29, 30].

The Revo-i surgical robot (Meere Company, Seoul, South Korea), the MiroSurge (Medtronic, Minneapolis, USA), the Hinotori Surgical Robot System (Medicaroid, Japan), the Single Port Orifice Robotic Technology – SPORT (Titan Medical Company, Toronto, Canada) are other robotic systems already available on the market or pending regulatory approval.

The very next phase of this evolution is the application of artificial intelligence to surgical robotic systems, with the aim of performing increasingly challenging procedures with safety and efficiency, while enhancing their ability to interact with complex environments and assist in the decision-making process. Completely automated surgical systems are at the moment, and will probably remain, only a theoretical perspective, but a new phase of robotic-guided, rather than robot-assisted surgery, has already started.

1.7 Conclusions

In recent decades, an exponential advancement in minimally invasive techniques has been observed, with the introduction of robotics representing one of the most remarkable events.

Despite the initial widespread criticism and rejection, robotic surgery's power to overcome the limitations of laparoscopy and offer a higher quality of surgery has made the approach a fully accepted surgical option. Its application to colorectal surgery showed safety and feasibility, as well as some operative advantages for surgeons, but clear benefits for patients are still far from being proven, partly because the speed of technology development often exceeds the ability of high-evidence studies to validate the results.

Longer operative times and expensive equipment leave some questions unanswered, but what yesterday was difficult to foresee has become a reality today, and it is not difficult to imagine that, as already happened with laparoscopy, the surgeons of tomorrow might not be able to perform certain procedures other than robotically.

The da Vinci system by Intuitive Surgical, which carries in its name the genius of Leonardo, represents the first and prominent actor of this revolutionary history but, with the progressive expiration of many patents, several potential competitors are starting to appear, pushing forward the boundaries of innovation.

References

1. Hæger K. The illustrated history of surgery. London: H. Starke; 1990.
2. Semm K. Endoscopic appendectomy. Endoscopy. 1983;15(2):59–64.
3. Litynski GS. Endoscopic surgery: the history, the pioneers. World J Surg. 1999;23(8):745–53.
4. Buess G, Hutterer F, Theiss J, et al. Das System für die transanale endoskopische Rectumoperation [A system for a transanal endoscopic rectum operation]. Chirurg. 1984;55(10):677–80.

5. Mühe E. Die erste Cholecystektomie durch das Laparoskop [The first cholecystectomy through the laparoscope]. Langenbecks Arch Chir. 1986;369:804.
6. Kwoh YS, Hou J, Jonckheere EA, Hayati S. A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery. IEEE Trans Biomed Eng. 1988;35(2):153–60.
7. Jacobs M, Verdeja JC, Goldstein HS. Minimally invasive colon resection (laparoscopic colectomy). Surg Laparosc Endosc. 1991;1(3):144–50.
8. Fowler DL, White SA. Laparoscopy-assisted sigmoid resection. Surg Laparosc Endosc. 1991;1(3):183–8.
9. Himpens J, Leman G, Cadiere GB. Telesurgical laparoscopic cholecystectomy. Surg Endosc. 1998;12(8):1091.
10. Marescaux J, Leroy J, Gagner M, et al. Transatlantic robot-assisted telesurgery. Nature. 2001;413(6854):379–80. Erratum in: Nature 2001;414(6865):710.
11. Weber PA, Merola S, Wasielewski A, Ballantyne GH. Telerobotic-assisted laparoscopic right and sigmoid colectomies for benign disease. Dis Colon Rectum. 2002;45(12):1689–94; discussion 1695–6.
12. Raison N, Khan MS, Challacombe B. Telemedicine in surgery: what are the opportunities and hurdles to realising the potential? Curr Urol Rep. 2015;16(7):43.
13. Satava RM. Surgical robotics: the early chronicles: a personal historical perspective. Surg Laparosc Endosc Percutan Tech. 2002;12(1):6–16.
14. Leal Ghezzi T, Campos CO. 30 years of robotic surgery. World J Surg. 2016;40(10):2550–7.
15. Davies BL, Hibberd RD, Ng WS, et al. The development of a surgeon robot for prostatectomies. Proc Inst Mech Eng H. 1991;205(1):35–8.
16. Stefano GB. Robotic surgery: fast forward to telemedicine. Med Sci Monit. 2017;23:1856.
17. Pugin F, Bucher P, Morel P. History of robotic surgery: from AESOP and ZEUS to da Vinci. J Visc Surg. 2011;148(5 Suppl):e3–8.
18. Carpentier A, Loulmet D, Aupècle B, et al. Chirurgie à coeur ouvert assistée par ordinateur. Premier cas opéré avec succès [Computer assisted open heart surgery. First case operated on with success]. C R Acad Sci III. 1998;321(5):437–42.
19. Atallah S, Parra-Davila E, Melani AGF, et al. Robotic-assisted stereotactic real-time navigation: initial clinical experience and feasibility for rectal cancer surgery. Tech Coloproctol. 2019;23(1):53–63.
20. Porpiglia F, Checcucci E, Amparore D, et al. Augmented-reality robot-assisted radical prostatectomy using hyper-accuracy three-dimensional reconstruction (HA3D) technology: a radiological and pathological study. BJU Int. 2019;123(5):834–45.
21. Hashizume M, Shimada M, Tomikawa M, et al. Early experiences of endoscopic procedures in general surgery assisted by a computer-enhanced surgical system. Surg Endosc. 2002;16(8):1187–91.
22. Delaney CP, Lynch AC, Senagore AJ, Fazio VW. Comparison of robotically performed and traditional laparoscopic colorectal surgery. Dis Colon Rectum. 2003;46(12):1633–9.
23. Giulianotti PC, Coratti A, Angelini M, et al. Robotics in general surgery: personal experience in a large community hospital. Arch Surg. 2003;138(7):777–84.
24. Pigazzi A, Ellenhorn JD, Ballantyne GH, Paz IB. Robotic-assisted laparoscopic low anterior resection with total mesorectal excision for rectal cancer. Surg Endosc. 2006;20(10):1521–5.
25. Vibert E, Denet C, Gayet B. Major digestive surgery using a remote-controlled robot: the next revolution. Arch Surg. 2003;138(9):1002–6.
26. Jayne D, Pigazzi A, Marshall H, et al. Effect of robotic-assisted vs conventional laparoscopic surgery on risk of conversion to open laparotomy among patients undergoing resection for rectal cancer: the ROLARR randomized clinical trial. JAMA. 2017;318(16):1569–80.
27. Peters BS, Armijo PR, Krause C, et al. Review of emerging surgical robotic technology. Surg Endosc. 2018;32(4):1636–55.
28. Huscher C, Marchegiani F, Cobellis F, et al. Robotic oncologic colorectal surgery with a new robotic platform (CMR Versius): hope or hype? A preliminary experience from a full-robotic case-series. Tech Coloproctol. 2022;26:745–53.

29. Morino M, Forcignanò E, Arezzo A. Initial clinical experience with a novel flexible endoscopic robot for transanal surgery. Tech Coloproctol. 2022;26(4):301–38.
30. Carmichael H, D'Andrea AP, Skancke M, et al. Feasibility of transanal total mesorectal excision (taTME) using the Medrobotics Flex System. Surg Endosc. 2020;34(1):485–91.