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REVIEW

Review of emerging surgical robotic technology

Brian S. Peters[1] · Priscila R. Armijo[1] · Crystal Krause[1] · Songita A. Choudhury[1] · Dmitry Oleynikov[1]

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Abstract

Background The use of laparoscopic and robotic procedures has increased in general surgery. Minimally invasive robotic surgery has made tremendous progress in a relatively short period of time, realizing improvements for both the patient and surgeon. This has led to an increase in the use and development of robotic devices and platforms for general surgery. The purpose of this review is to explore current and emerging surgical robotic technologies in a growing and dynamic environment of research and development.

Methods This review explores medical and surgical robotic endoscopic surgery and peripheral technologies currently available or in development. The devices discussed here are specific to general surgery, including laparoscopy, colonoscopy, esophagogastroduodenoscopy, and thoracoscopy. Benefits and limitations of each technology were identified and applicable future directions were described.

Results A number of FDA-approved devices and platforms for robotic surgery were reviewed, including the da Vinci Surgical System, Sensei X Robotic Catheter System, FreeHand 1.2, invendoscopy E200 system, Flex® Robotic System, Senhance, ARES, the Single-Port Instrument Delivery Extended Research (SPIDER), and the NeoGuide Colonoscope. Additionally, platforms were reviewed which have not yet obtained FDA approval including MiroSurge, ViaCath System, SPORT™ Surgical System, SurgiBot, Versius Robotic System, Master and Slave Transluminal Endoscopic Robot, Verb Surgical, Miniature In Vivo Robot, and the Einstein Surgical Robot.

Conclusions The use and demand for robotic medical and surgical platforms is increasing and new technologies are continually being developed. New technologies are increasingly implemented to improve on the capabilities of previously established systems. Future studies are needed to further evaluate the strengths and weaknesses of each robotic surgical device and platform in the operating suite.

Keywords Robotic surgery · Surgical robotics · Laparoscopy · Endoscopy · Robotic-assisted surgery

As the trend in general surgery moves toward less invasive procedures, there has been an increase in the use of laparoscopic and robotic procedures. Laparoscopy has helped tremendously in reducing patients' scarring and hospitalization time [1]. In some cases, it has also limited the surgeon's dexterity, sensory feedback, and visualization, relative to open procedures. The development of surgical robotic systems has continued to address those limitations that laparoscopic surgery potentially places on the surgeon [2, 3].

Minimally invasive Robotic-assisted Surgery (RAS) has become an avenue to integrate current technology advancements in traditional minimally invasive surgery. As laparoscopy continues to gain ground, a push to develop surgical systems that deploy laparoendoscopic single-port surgery (LESS) instruments has followed [4]. Furthermore, as natural orifice translumenal endoscopic surgery (NOTES) has grown in popularity, developers have focused on producing congruent robotic platforms. For instance, the master and slave transluminal endoscopic robot (MASTER) platform seeks to expand user control dexterity, instrument sensory feedback, and location triangulation, which have the potential to increase procedural capabilities in NOTES. Surgeons who continually search for procedures and technology to improve outcomes, and leave patients with no visible scars, support this effort [5]. However the benefits brought forth by advancements in the physical capabilities of RAS systems must be supported by data before widespread adoption is

✉ Dmitry Oleynikov
doleynik@unmc.edu

1 University of Nebraska Medical Center, 986245 Nebraska Medical Center, Omaha, NE 68198-6245, USA

realized and the potential to progress current practice using emerging technologies is limited by the results of their implementation.

Setting the bar for robotic-assisted surgery in 2000, the da Vinci® Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA; Fig. 1) has grown to become one of the most commonly used robotic surgical systems [5]. As of 2015, over 3400 systems were in use around the world [6]. Since its inception, the system has been cleared for a variety of procedures including cardiac, colorectal, general, gynecologic, head and neck, thoracic, and urologic surgery [3]. In its wake has followed a breadth of unique systems, which aim to find their niche in an expanding market heretofore dominated by the da Vinci. For instance, the Senhance robotic platform is a console similar to da Vinci with multiple manipulator arms controlled from a remote station via laparoscopic handles providing multiple degrees of freedom (DOF). However, unlike the da Vinci system whose haptic feedback is via visually displayed cues, the Senhance platform provides actual tactile haptic force, allowing the surgeon to feel forces generated at the distal end of instruments while handling tissue. Additionally, the Senhance incorporates a novel eye-tracking technology, which centers the camera image at the point the surgeon is looking at, as opposed to the da Vinci, which uses a binocular display controlled by a footswitch panel [7]. Utilization of new technologies in this fashion may provide newly developed platforms the necessary edge to acquire a portion of market share. Another robotic platform seeking greater utilization in the operating suite is the Flex Robotic System. Flex is a single-port (SP) flexible endoscope for use in laparoendoscopic single-port surgery (LESS). Separating itself technically from the da Vinci SP, the Flex system is capable of defining a non-linear path to surgical sites that is allowed by advancing a flexible outer mechanism through which inner channel instruments are deployed. This is in contrast to da Vinci's line-of-sight based platform, and may allow for enhanced access relative to non-flexible straight approaches.

The use of robots in surgery has made tremendous progress in a relatively short period of time, realizing improvements for both the patient and surgeon. For the patient, there has been a reduction in hospitalization time, fewer complications, and less scarring [1]. The surgeon has seen benefits in ergonomics, including consoles that allow them to sit while operating, joystick controls which compensate for the fulcrum effect from the use of laparoscopic tools, and 3D glasses displaying magnified views of the procedure. Another example of engineering applied to medicine is the integration of haptic devices, which receive information from distal sensors and feed them back to the surgeon to allow for careful manipulation of tissues. This is achieved through torque and force sensors in the instrument tip that relay information including grasping force back to the user. Intraperitoneal surgical robots are also being optimized for minimally invasive surgical use and improved intraoperative surgical triangulation [8]. Procedurally, surgical robotic technology has had a transformative impact via the automation and teleoperation of robotic platforms. Furthermore, greater dexterity and precision as well as increased visualization and better control and stability of instruments has been obtained through improved optics and display modalities.

The purpose of this review is to explore current and emerging surgical robotic technologies in a growing and dynamic environment of research and development. This article describes currently available devices, identifies their benefits and limitations, and describes applicable future directions. The systems featured in this review are applicable to general surgery, and a summary of all the technologies discussed is shown in Table 1.

FDA-approved platforms

Da Vinci surgical system

The *da Vinci* Surgical System's latest model, the Xi (Intuitive Surgical, Inc., Sunnyvale, CA; Fig. 1), is composed of a master console and a mobile platform with four boom-mounted robotic arms. Each arm is capable of three DOF

Fig. 1 The *da Vinci*® Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA) [5]

Table 1 Comparison of surgical robotic technologies

Device	Robotic endoscopic surgery purpose	Phase	FDA status	Company	Robotic segments	DOF/segments	Visual	Interface	Additional
da Vinci surgical system	Urologic, laparoscopic, gynecologic, general non-cardiovascular thoracoscopic, thoracoscopically assisted cardiotomy	Commercially available	Approved	Intuitive Surgical Inc	4	3 + 7/wrist	2 HD–3D	Master–slave finger loops	Tremor filtration
Sensei X robotic catheter system	Cardiac catheter insertion	Commercially available	Approved	Hansen Medical Inc	2	3	3D, ICE, Fluoroscopy	Master–slave joystick	Haptic feedback, navigation
FreeHand v1.2	Camera control: laparoscopy	Commercially Available	Approved	Freehand 2010 Ltd	1	3	HD–3D	Headset	Laser guidance
Invendoscopy E200 system	Colonoscopy	Commercially available	Approved	Invendo Medical GmbH	1	180°	HD	Master–slave joystick	Aseptic single use
Flex® robotic system	Transoral: oropharynx, hypopharynx, larynx	Commercially available	Approved	Medrobotics Corp	2	180°	HD–2D	Joystick	Telescopic inner-outer mechanism
Senhance	Gynecologic, laparoscopy	FDA anticipated	Approved	TransEnterix	3	7	HD–3D	AR/VR controllers	Haptic feedback, eye-sensing camera
ARES	Bronchoscopy	Clinical trial	Approved	Auris Surgical Robotics	2	6	U	Controllers	Endoluminal
Single-port instrument delivery Extended research (SPIDER)	Instrument delivery: LESS	Acquired	Approved	TransEnterix	2	Multiple	U	Finger loops	Umbilicus access
NeoGuide Colonoscope	Colonoscopy	Acquired	Approved	Intuitive Surgical Inc	16	1	U	U	3D mapping
MiroSurge	Laparoscopy	Commercially available	NA	DLR robotics	5	7	HD–3D	Master slave Sigma.7	Haptic feedback
ViaCath System	NOTES	Commercially available	NA	BIOTRONIK	1	9	N/A	Push–pull steering	Haptic feedback
SPORT™ surgical system	LESS	FDA pending	NA	Titan Medical Inc	1	multiple	HD–3D	Controllers	Multi-articulated instruments
SurgiBot	LESS	FDA resubmission	NA	TransEnterix	2	6	HD–3D	Controllers	Internal triangulation

Table 1 (continued)

Device	Robotic endoscopic surgery purpose	Phase	FDA status	Company	Robotic segments	DOF/segments	Visual	Interface	Additional
Versius robotic system	Upper GI, gynecological, colorectal, renal	Cadaveric trial	NA	Cambridge medical robotics	1 (modular)	7	HD–3D	Controllers	Haptic feedback
MASTER	NOTES	Clinical trial	NA	Nanyang Technological University	2	9		Controllers	Haptic feedback, reconstruction navigation
Verb surgical	Advanced	Development	NA	Alphabet	U	U	U	U	U
Miniature in vivo robots (MIVR)	Advanced	Development	NA	CAST	2	6	HD	Controllers	Miniaturized
Einstein surgical robot	Bariatric, thoracic, colorectal, urologic, general	Development	NA	Medtronic	U	U	U	U	U

Degrees of freedom (DOF), unreported (U), not approved (NA)

and able to manipulate the proprietary EndoWrist instrument, which provides an additional seven DOF by mimicking the movements of the human wrist [9]. The master console is equipped with two cameras that together provide a magnified HD–3D view of the surgical field [10]. The slave is controlled via master–slave finger-cuff telemanipulators, which were designed to allow the user to be rapidly trained [6].

The master console was created with the surgeon's needs in mind; it has adjustable finger loops on the telemanipulators, adjustable intraocular distance, and a padded headrest and arm bars [5]. Instrument motion is made possible through cable-driven joints at the distal end of the instrument [10]. The system achieves its precision through high-resolution 3D visualization, tremor filtration, motion scaling, and a comfortable user interface [5, 10].

The da Vinci Surgical System is well suited to act as a prototype in discussion regarding utilization of robotic surgical systems; current clinical application, procedural data generated, and overall literature volume of the da Vinci Surgical System far surpasses its competitors. Therefore, this section will focus on robotic-assisted procedures utilizing da Vinci in place of open surgery and conventional laparoscopy.

Currently, data suggest an overall trend for conversion from open surgery to robotic-assisted surgery in procedures such as colectomy, cholecystectomy, inguinal hernia repair, ventral hernia repair, and bariatric surgeries [11]. From 2008 to 2015 across more than 300 academic medical centers and affiliated hospitals, there was a significant increase in da Vinci-assisted surgeries in inguinal and ventral hernia repairs. Additionally, the volume of open surgery in colectomy, cholecystectomy, and bariatric surgery decreased simultaneously with a reported increase in robotic-assisted surgery utilization in those procedures [11]. Conversion from open to robotic technique has been facilitated by the da Vinci's 3D visualization, wristed instruments with motion scaling and tremor reduction. These characteristic abilities of the da Vinci Surgical System seek to build on the widely reported ability of minimally invasive surgery to improve outcomes while reducing infection, readmission, and length of stay postoperatively [12–14]. Although the workload placed on the da Vinci is a fraction of total procedures relative to open and conventional laparoscopic procedures, the overall increase in robotic technique utilization has been attributed to expanding availability and variety of systems [11]. Additionally, the marked increase in utilization of the da Vinci Surgical System is exemplified by a relative tenfold increase in its use for cholecystectomies and colectomies during a 7-year evaluation [11].

The majority of systems currently available and under development likely seek to mirror the success of the da Vinci Surgical System. Surgeons who support the utilization of robotic-assisted approaches in their practice may have previous exposure to the da Vinci Surgical System, thereby decreasing the initial learning curve experienced while implementing newer technologies. Additionally, a significant barrier to the incorporation of robotic-assisted systems such as the da Vinci is the cost per procedure relative to open and conventional laparoscopic surgeries. One study found that procedures utilizing the da Vinci were less expensive than open surgery; a finding attributed to the longer length of stay and additional costs associated with the latter [15]. Although da Vinci may reduce costs compared to open procedures, the same benefit over conventional laparoscopy has not been shown; the cost of supplies and instruments associated with the da Vinci were cited as a contributing factor [16].

There are several hurdles that have limited the advancement of this technology including the cost of the robot and instruments, lack of haptic feedback (which gives the user a sense of touch), the size of the system, and the inability to quickly switch instruments during a procedure [3, 10].

Sensei X robotic catheter system

The Sensei X robotic catheter system (Hansen Medical Inc., Mountain View, CA; Fig. 2) is a cardiac catheter insertion device [17]. The system is controlled by an electromechanical slave guided by a computerized master, which translates the user's movement via an external handle located at a remote workstation [18]. Manipulation allows freedom of motion and the ability to maneuver in three dimensions. The slave contains an 8 Fr inner leader capable of 275° articulation, with an outer sheath capable of 90° articulation [19]. The motion of each component is controlled by pull-wires via a remote joystick or buttons on the master console [20]. The robotic catheter manipulator can support several different catheters within its guide catheter [18].

The Sensei X is unique in several ways; the tip of the catheter can be moved in three dimensions via remote control and is coupled to a robotic navigation system that measures the forces at the distal tip. These haptic vibrations are then translated to the user via the controller. Information is integrated and displayed visually on multiple workstation imaging monitors, including 3D mapping, ICE, fluoroscopy, and EKG recordings [18]. Additionally, the function of sensing grams and direction of contact force via the IntelliSense™ sensor system allows quantification of the force applied by the catheter tip [21]. This device has been successful for use in cardiac mapping, ablation, and endovascular aneurism repair [20]. A clinical trial of 100 patients which used the Sensei X for catheter ablation in atrial fibrillation took place in Prague, Czech Republic, in 2011. In this trial, 100% of pulmonary veins were acutely isolated, freedom from subsequent atrial fibrillation was successful in 63% of cases, and zero complications were reported after a median 15-month follow-up [22].

Although compatible with a variety of procedures, the required sheath may increase the risk of cardiac perforation [23]. In addition, the large size, high cost, and relatively long setup time limit the system. FDA approval was obtained in 2007.

FreeHand v1.2

FreeHand 1.2 (FreeHand 2010 Ltd., Cardiff, UK; Fig. 3) is a robotic camera controller developed for minimally invasive surgery that enables the user to control the camera hands-free. This system is composed of a lockable articulating arm,

Fig. 2 Sensei® X (Hansen Medical, Mountain View, CA) [17]

Fig. 3 Freehand®, a next generation endoscope holder (Freehand® 2010 Ltd., Cardiff, UK) [17]

an electronic control box, and a robotic motion assembly unit [24]. Mounted on railings around the operating table, the camera can be moved in three dimensions, controlled via operator head movements, and laser-pointed guidance [4, 17]. The camera operator wears a small lightweight headset or surgical cap containing an infrared transmitter that sends a signal to a receiver on the monitor. To select the direction of movement, the operator moves his/her head in the desired direction; an LED arrow with the selected direction will be displayed. In order to initiate movement, a foot switch is pressed until the camera is in the desired location; releasing the switch will terminate movement [24]. After choosing the desired combination of pan and tilt, actuating the movement, and releasing the pedal, the scope maintains its position. Additional functions include zoom, speed of movement adjustability, and position memory to allow scope retraction and reinsertion retaining field of view.

Device functionality decreases dependence on an assistant due to the surgeon's ability to control all camera movements without halting the operation. Another advantage is the capability of transferring the headset between personnel without interruption or reconfiguration of the system. The system is often preferred due to its fast and easy installation, minimal training for use, compact size, and precise and accurate movement. Training has been shown to result in effective skill acquisition after three repetitions [25].

FreeHand v1.2 is commercially available and currently in use for a variety of procedures worldwide including urological, gynecological, and general surgery. In 2010, a study was performed including 16 patients undergoing robotic-assisted single-port inguinal hernia repair using the FreeHand camera controller. FreeHand out performed conventional unilateral LESS repairs in the number of times scope cleaning was necessary, total time spent cleaning the scope, and total duration of surgery. No wound infections were reported, and outcomes were shown to have no post-operative failures [26]. FreeHand has improved considerably over its predecessor the EndoAssist. However, the device response may be sub-optimal in several instances: when moving in the vertical direction, if someone other than the surgeon is operating the camera, or if the ergonomics of the head movement control interface is not desirable [4, 24]. FDA approval was obtained in 2009.

Invendoscopy E200 system

The invendoscopy E200 system (Invendo Medical GmbH, Germany; Fig. 4) is composed of a reusable handheld controller and processing unit, as well as a single-use sterile colonoscope [27]. It is operated by manual insertion for visualization, diagnostics, and therapeutic endoscopic surgery. Individually packaged, the scope and its components are sterile and allow an aseptic setup in order to prevent transmitting infection [28]. The robotically assisted colonoscope has a 170 cm insertion length, with a tip that can be deflected 180° in all directions. A 35 mm bending radius allows retroflection and visualization of the colon. In addition, maneuvers with standard flexible instruments are possible due to its 3.1 mm working channel.

The handheld controller (invendo ScopeController) is a lightweight joystick, which is detachable from the colonoscope (invendo SC200). The controller's low profile, integral buttons, and ergonomic design reduce the musculoskeletal burden on the operator, while maintaining conventional colonoscope functions. Tip deflection, insufflation, suction, and image capture can be operated using one hand. The HD camera consists of three white-light LEDs and a complementary metal oxide semiconductor (CMOS)-imaging chip [27, 29]. Images are processed with the SPU E200 graphical user interface. Maintenance, data entry, and setup functions are accessed via a touchscreen device. FDA approval was obtained in 2016.

In a 2011 feasibility study of intubation rates using Invendo Medical technologies, the safety and efficacy of computer-assisted robotic colonoscopy was reported. In healthy volunteers aged 50–70 years, carbon dioxide insufflation or water instillation on demand was initiated without sedation. The rate of intubation was reported at 98.4%, with 95.1% sedation-free completion. Additionally, no device-related complications were experienced [27].

Flex® robotic system

The Flex® robotic system (Medrobotics Corp., Raynham, MA; Fig. 5) is a single-port operator-controlled flexible

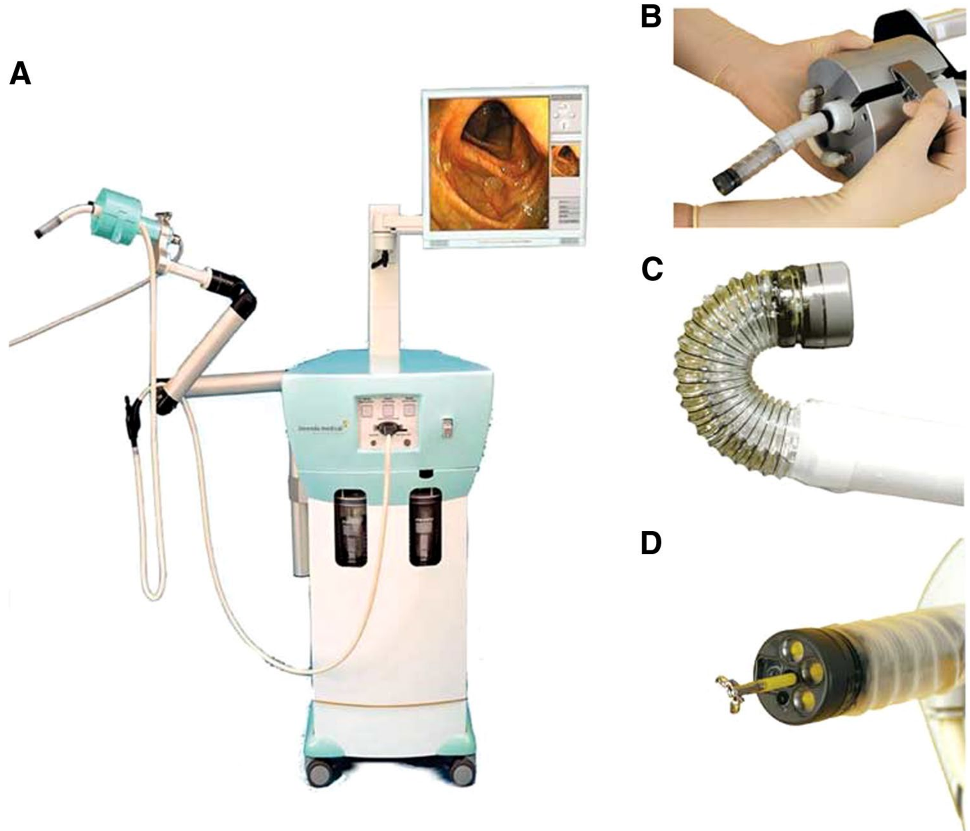

Fig. 4 The SC20 colonoscope. Invendoscopy E200 system. This figure shows **A** the complete system, **B** the tip introduced through the driving motor, **C** the tip in full flexion, **D** the tip with biopsy forceps shown through the working channel. (Invendo Medical GmbH) [27]

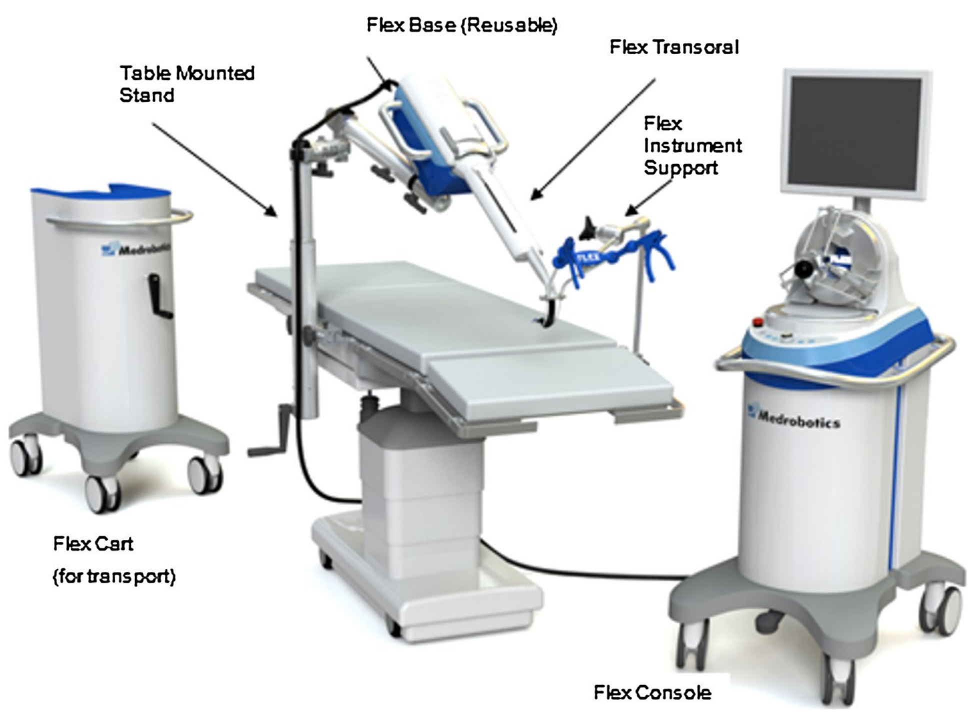

Fig. 5 Medrobotics Flex™ System (Flex System, Medrobotics Corp., Raynham, MA) [30]

endoscope adapted for minimally invasive transoral surgery of the oropharynx, hypopharynx, and larynx [30, 31] Its design allows the surgeon to specify a path around anatomical structures by steering a robotic outer mechanism, through which an inner mechanism follows. An operational tower console consists of a touchscreen, magnified HD two-dimensional visual display, and a joystick controller. The system can articulate at nearly 180°, and allows 3 mm articulating instruments to be operated via joystick [32].

The snake-like flexible scope includes an inner and outer segment with a single point of articulation between adjacent segments [30]. Each segment can be placed in a semi-rigid or flexible state while manipulated and steered in a non-linear self-supported path. Moreover, the endoscope has two lumens that provide a pathway for electrical connections or an irrigation tube. The two flexible guide tubes, called External Accessory Channels (EAC), allow utilization and exchange of compatible flexible instruments during procedures [30, 33]. The multi-linked concentric mechanism with working channels accommodates instruments such as scissors, needle driver, grasper, and dissector. A camera receives illumination from six light-emitting diode lights on its tip, and can be moved vertically, horizontally or within its own axis, providing a wide visualization for the endoscopist. Digital zoom functionality provides magnification of the image [30, 33].

Utilization of the system in cadavers has shown good visualization of the oropharynx, hypopharynx, and larynx by the robot, and has verified the system's ability to overcome the disadvantages of standard rigid instruments [7, 33]. Additionally, use in cases with patients who underwent head and neck surgery has demonstrated the safety and feasibility of the system, especially due its capability of reaching difficult anatomic areas [30, 31]. In a 2015 clinical study at the University Hospital Essen in Germany, 40 patients with lesions of the oropharynx, hypopharynx, or supraglottic larynx underwent surgical resection using the Flex Robotic System. Of those, 95% of the lesions were successful with zero adverse events reported [34]. FDA approval was obtained in 2015.

Senhance

Senhance (TransEnterix, Morrisville, NC; Fig. 6) is a console type robotic platform consisting of a remote control station unit, manipulator arms, and a connection node [35, 36]. The robot system comprises three arms, each individually mounted on its own cart [37]. Laparoscopic style handles provide haptic feedback from the cable-actuated arms, which provide 7 DOF [37].

The system's design incorporates a remote HD–3D-technology display coupled with an eye-tracking camera control system, which centers the image at the point the surgeon is looking at. While pressing buttons on the handles, the surgeon can control the zoom by moving his or her head forward and backward relative to the display monitor. The implementation of eye-tracking technology is an evolution of current visualization technologies, such as the da Vinci Surgical System's binocular display controlled by foot-operated

Fig. 6 Senhance robotic console and operating system (TransEnterix, Morrisville, NC) [36]

switches. An incorporated haptic interaction, in addition to a scaled 1:1 force feedback, allows the surgeon to manipulate the instruments with amplified sensed forces and to perceive tissue consistency and the stress exerted by the instruments. This tactile force feedback translates sensation from an instrument's distal end to the surgeon's hand, contrasting da Vinci's feedback, which is displayed visually rather than felt at the controller. The laparoscopic instruments, mostly reusable, are attached via magnets, facilitating their replacement during surgery [35, 36, 38].

Senhance has been successfully used in clinical gynecological surgeries such as hysterectomy [35, 37, 38]. Furthermore, in a 6-month study of 45 patients requiring surgery for inflammatory bowel disease, colorectal cancer, adenoma, and complicated diverticular disease, Senhance was shown to be feasible and safe; three procedures were converted to standard laparoscopy, with postoperative complication rates reported as 35.5% [39]. In November 2017, The Florida Hospital Institute for Surgical Advancement became the first site in the U.S. to purchase the Senhance robotic system for commercial use in minimally invasive surgery [40].

One of the disadvantages of the system is the large size of the equipment, requiring considerable space in the operating room. Moreover, the robot platform lacks articulated instruments, limiting its applicability in more complex procedures. Additionally, use of polarizing glasses is required with the 3D-monitor eye tracking [37]. Still, authors have shown it to be comparable to standard laparoscopic counterparts [36]. Formally ALF-X of SOFAR S.p.A. FDA approval gained in October 2017.

Auris robotic endoscopy system (ARES)

Auris robotic endoscopy system (ARES; Auris Surgical Robotics, Silicon Valley, CA, USA; Fig. 7) is a teleoperated endolumenal bronchoscope designed to clarify the

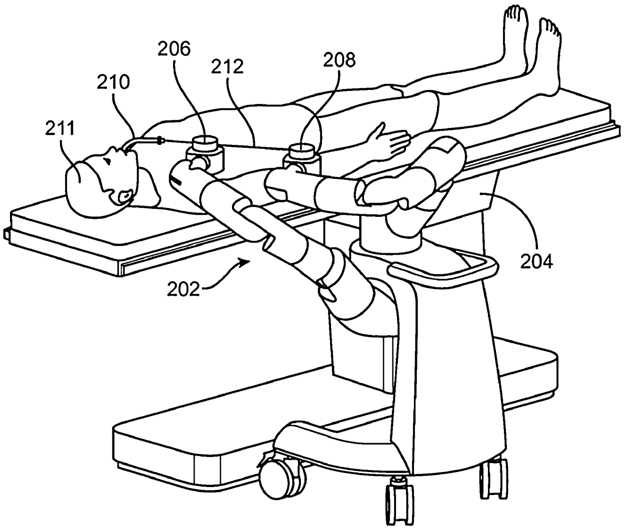

Fig. 7 Auris robotic endoscopy system (ARES), artist's rendering from Auris's patent application, Source: United States Patent and Trademark Office (Auris Surgical Robot, Silicon Valley, CA) [42]

visualization of the respiratory tract during bronchoscopy [41]. It consists of a surgeon console, controller cart, patient-side system, and bronchoscope.

This patient-side system is made up of a robot cart, robot arms, as well as camera controls and power boxes. The robot has two arms, each with six DOF, and an Instrument Drive Mechanism with four axes of actuation. A flexible bronchoscope with articulated tip can be attached at the end effector of the arm, and the design allows an endoscopist to bend the bronchoscope in four directions. Moreover, the working channels can be used for standard procedures, such as irrigation and aspiration [41].

In a 2014 clinical trial in San Jose, Costa Rica, in diagnostic bronchoscopies on 15 patients with respiratory lesions, we completed using ARES. Successful navigation without adverse effects was reported in all cases [43]. FDA approval was obtained in 2016.

NeoGuide colonoscope

The NeoGuide Endoscopy System (NeoGuide Endoscopy System Inc, Los Gatos, CA; Fig. 8) is a computer-aided colonoscope that utilizes computerized mapping to travel along the natural curves of the colon, resulting in less force applied to the walls of the organ [44]. The system decreases colonic looping in order to perform endoscopy without sedation; it uses a programmable overtube that prevents the reformation of colonic loops once endoscopically reduced [45]. Real-time 3D mapping of the colon enables viewing the position of the scope, identifying loops, and identifying anomalies in pathology. It is intended for use in lower GI endoscopy and interventions, providing enhanced access and visualization [44].

The scope is composed of sixteen equally sized electromechanically controlled segments. Each segment is

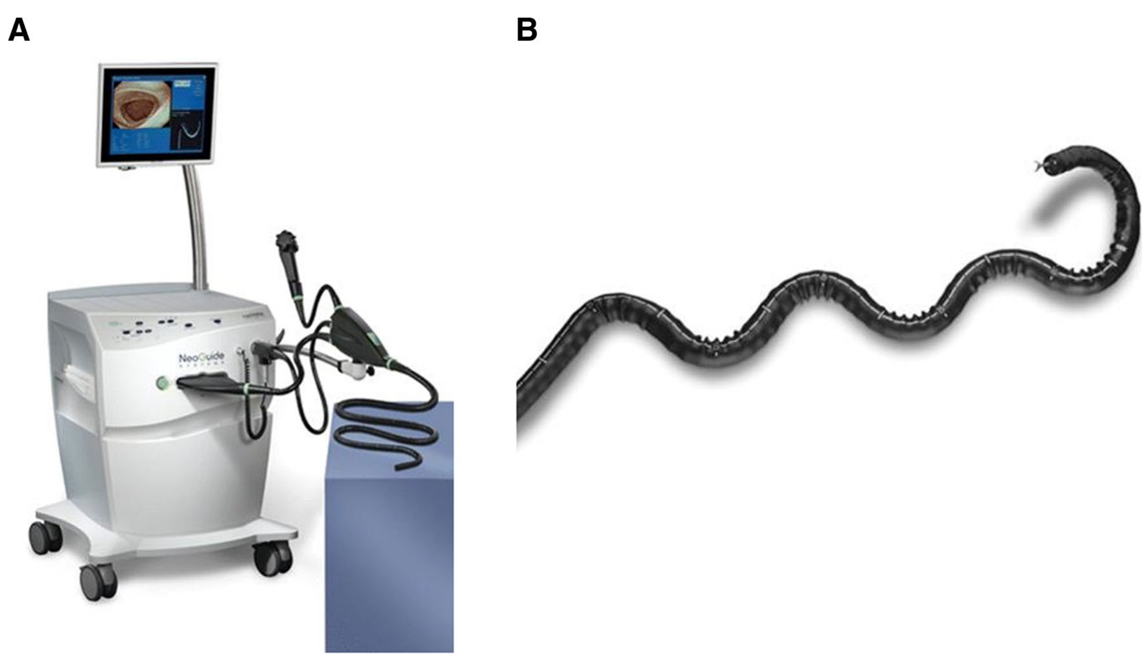

Fig. 8 NeoGuide™ Endoscopy System. **A** The console system contains the video, light, and insufflation functions and the motors controlling the segments in the insertion tube. **B** The insertion tube with multiple segments that allow the scope to navigate the colon (NeoGuide™ Systems Inc.) [44]

manipulated by an actuation controller and follows the natural shape of the colon using an algorithm that determines its precise anatomical position [28]. As the scope is advanced the articulating segments take on the angle and shape of the distal tip as they "follow-the-leader" negotiating through colonic flexures [28, 45]. The design has resulted in an immense reduction of the pressure and force applied to the colon walls, and the tip can be guided to the left, right, down, up, or a combination of directions [44]. One user can operate the system in two available modes: passive or active. In passive mode, the colonoscope is relatively stiff although more flexible than a standard scope. In this mode of operation, it is primarily used for therapies and biopsies. In active mode the scope relays information from the user's commands to the actuation controller. The tip of the device has an internal position sensor that measures the commands from the user as well as an external position sensor that measures the scope's insertion depth. In a human clinical feasibility trial for unsedated colonoscopy, ten consecutive procedures successfully reached the cecum. The study reported visualization of pathology such as diverticular disease and colonic polyps with no complications, no adverse effects, and high patient and physician satisfaction [46]. FDA approval was obtained in 2006. Intuitive Surgical acquired NeoGuide Systems Inc. in 2009.

NON-FDA-approved platforms

MiroSurge

MiroSurge (RMC, DLR, German Aerospace Center, Oberpfaffenhofen-Weßling; Fig. 9) is a telemanipulated minimally invasive robotic surgery (MIRS) system currently under development. The system incorporates 3–5 individual instrument carrying minimally invasive robot-assisted (MIRO) arms that allow multiple modes of control, the capacity to utilize various devices, and the ability to be mounted to various locations on table rails [17, 47].

A height adjustable master control console and an autostereoscopic display are the central components of the MiroSurge system. Configurations allows three to five MIROs to be used: two for guiding instruments via dedicated left and right manipulation, and one for guiding the endoscopic camera [49]. Each MIRO arm accommodates seven DOF, which gives the user a variety of manipulation configuration options [49]. Furthermore, the MIRO arms can be commissioned to a variety of uses including actuated surgical instrumentation adding additional DOF (MICA) and HD stereo/video laparoscopy [47]. The MIRS instruments are equipped with haptic devices, and the surgeon is able to view all information via the master console 3D-display [47, 50].

Although primarily a teleoperated master–slave robotic system, a soft robotics feature enables the surgeon to manually shift and position the robot arms. This is possible due to the joints of the MIRO arms, which contain torque and position sensors; the robot can be operated in impedance-controlled mode. Here, the points of insertion are planned prior to surgery with assistance from algorithms that account for the kinematics of the robot [49].

The system has been used extensively for endoscopic teleoperated minimally invasive procedures and open surgeries in the abdomen and thorax [49]. MiroSurge is in development at the Robotics and Mechatronics Center (RMC), a multi-institutional cluster entity of the Federal Republic of Germany national aeronautic, space research, and project management center. It is speculated that the MiroSurge technology has been licensed for use in applications that will be announced imminently [47]. During publication, no information on FDA approval was available.

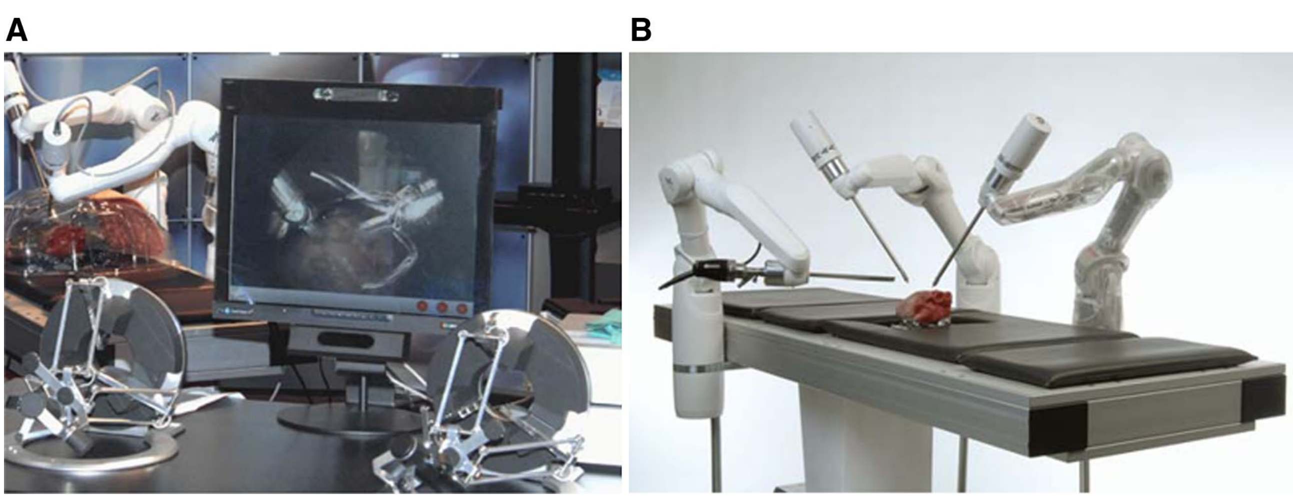

Fig. 9 **A** The DLR MiroSurge user interface, **B** robotic system (DRL, German Aerospace Center) [48]

ViaCath system

The ViaCath system (BIOTRONIK, Berlin, Germany; Fig. 10) is a steerable flexible diagnostic catheter [3, 51]. It is a teleoperated endoscopic robot, composed of a master console and slave with long-shafted instruments that run along a standard colonoscope or endoscope via a flexible articulated overtube [3, 51]. Designed for NOTES, its haptic interface and interchangeable instruments provide procedural precision [52].

Electronically controlled narrow bore instruments with end effectors such as a grasper, scissors, electrocautery knife, and a needle holder have been specifically designed for this system [3, 52] The instrument shafts are constructed with stainless steel and Teflon to create increased flexibility and reduce friction. The instruments, along with the positioning arm, have seven DOF, which are controlled by 14 tension cables [52]. The overtube itself has two joints in series, which provide two additional DOF for a total of nine when in combination with the positioning arm [46]. The overtube is responsible for properly situating the endoscope and the two channels used by the instruments; the instruments are oriented in a triangular fashion via a nose cone. The nose cone contains cable-actuated gripper devices which allow for increased rotary motion [52]. Surgeon guided motion to catheter tip movement, in a 1-to-1 ratio, function to increase maneuverability [53].

Limitations include inappropriate spatial orientation immediately upon entering the peritoneal cavity, lack of full triangulation due to parallel orientation of instruments, and manipulation forces smaller than the instruments used in traditional laparoscopic surgery [51]. Reports describe 3 N force transmissions, which may negatively impact controlled manipulation of the device [46], developed by endoVia Medical, acquired by Hansen Medical, currently available from BIOTRONIK. During publication, no information on FDA approval was available.

SPORT™ surgical system

A console-based platform for LESS, the Single Port Orifice Robotic Technology (SPORT) Surgical System (Titan Medical Inc., Toronto, Ontario; Fig. 11) is composed of a workstation and robotic platform controlled by the surgeon via hand controllers, foot pedals, and a touchscreen [4, 54]. The workstation allows the surgeon to interact with the robotic platform, including a 3D–HD endoscopic view via fiber-optic illuminated images displayed on a high-definition flat-screen monitor [37, 54].

The design utilizes a collapsible system that can be inserted into the body cavity through a 25 mm incision. After the system is inserted, it is manipulated into place and controlled remotely. The device was developed with multi-articulated instruments using single-use replaceable tips, an ergonomic workstation, and a mobile patient cart. The system has been shown to be successful in single-port nephrectomy in animal models [37]. SPORT is not for sale in the United States, FDA approval pending.

SurgiBot™

The SurgiBot™ (TransEnterix, Morrisville, NC; Fig. 12) is a robotic surgery system undergoing development. A patient-side minimally invasive device, the system is being developed to provide underserved populations surgical robots with minimal acquisition investment [2, 55].

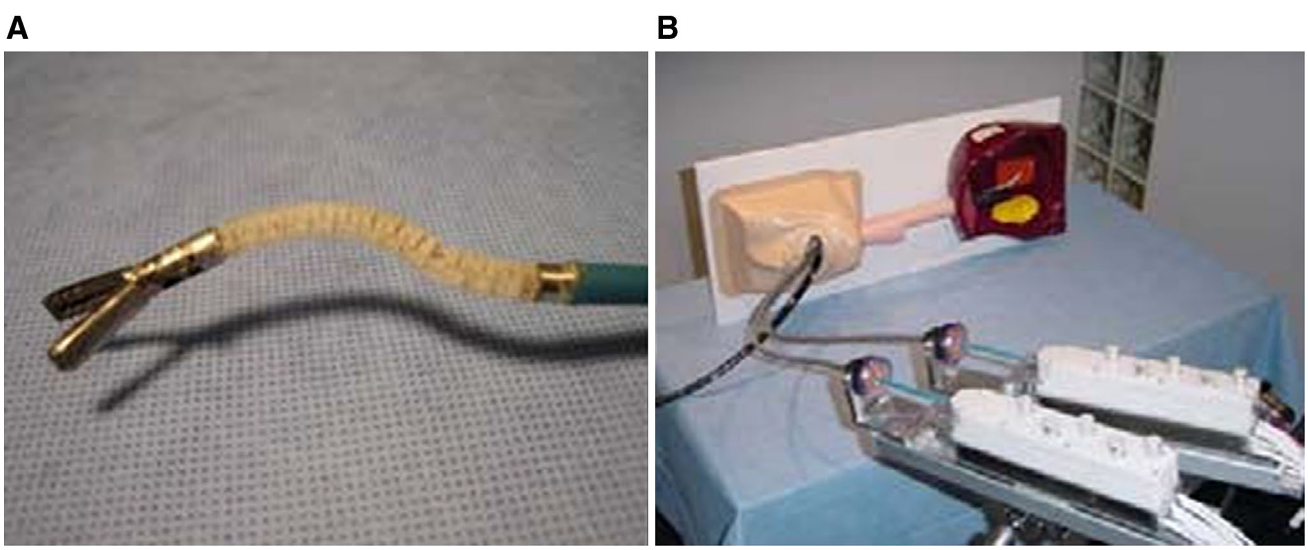

Fig. 10 ViaCath System. **A** The flexible instrument with fixed end effectors. **B** External actuators (endoVia Medical) [52]

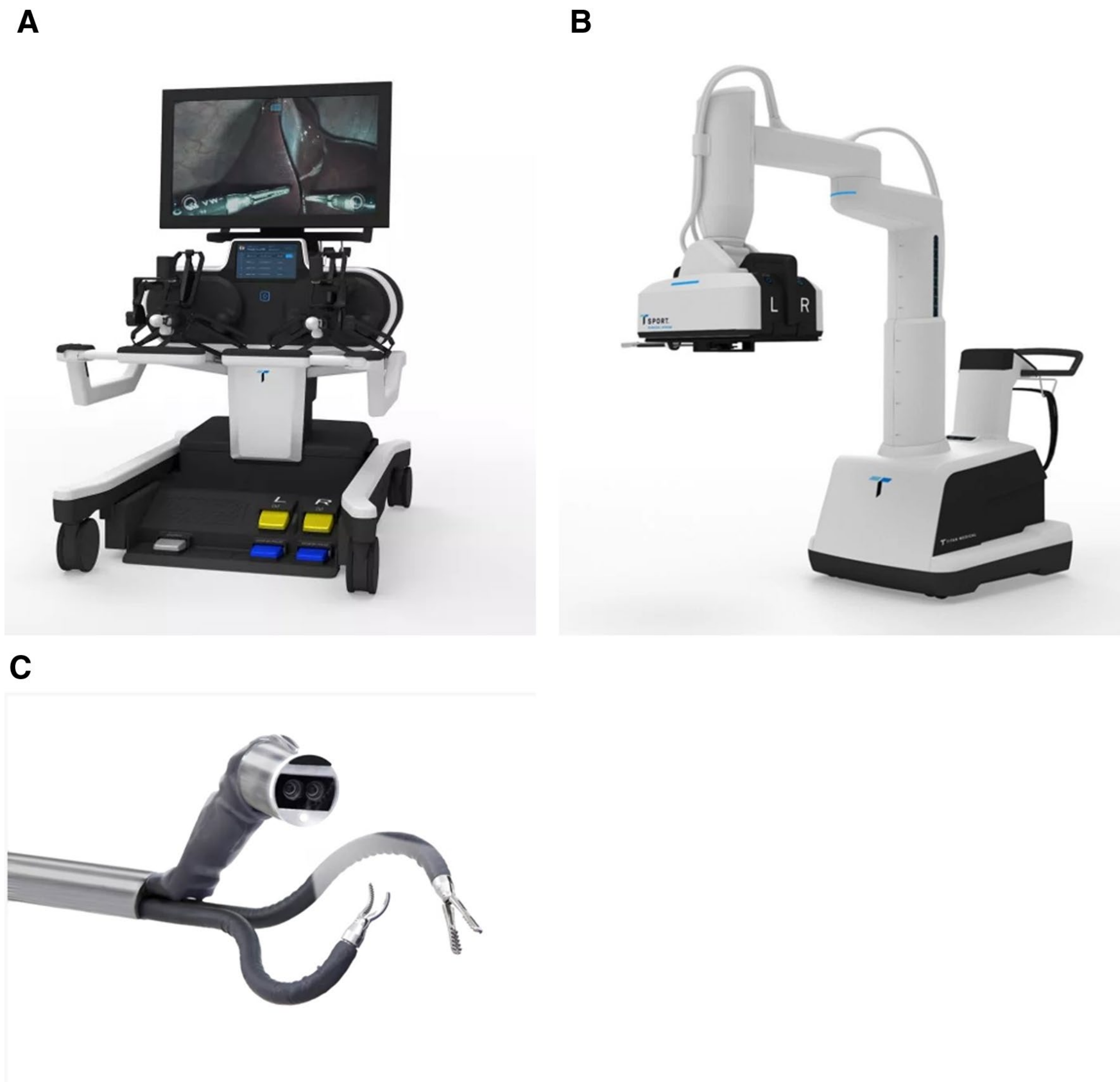

Fig. 11 Single Port Orifice Robotic Technology (SPORT™) robotic system. Shown (clockwise left to right) is the robotic console, surgical robot, and the multi-articulated instruments with end effectors (Titan Medical Inc., Toronto, Ontario) [2]

The system provides surgeons with controlled flexible instruments inserted through a single-incision site. The robotic system allows for several instruments to be placed through the channel into the operating space, with functionality including 3D vision, ergonomic operating controls, and precision movement with scaling. The device is being developed to provide a less expensive approach to robotic surgery utilizing internal triangulation, 3D vision throughout the operating field, and close proximity of the surgeon to patient [55]. In a 2015 pre-clinical trial in the porcine model, SurgiBot was shown to be successful in several general surgery and urology procedures at Baptist Health Medical Group in Miami, Florida [56]. SurgiBot is not available in any market; approval by the FDA was denied in April 2016 with resubmission to follow.

Much of the technology implemented in the previously described SurgiBot was gleaned in the development of the Single-Port Instrument Delivery Extended Research (SPIDER) system (TransEnterix Durham, NC; Fig. 13). SPIDER was created to give general surgeons LESS access through smaller diameter incisions, and allow angles of articulation that could not be achieved by other single-site techniques [57].

SPIDER consists of four working channels that are contained in a single port that gains access to the abdominal cavity through the umbilicus. The two static channels and two flexible channels allow tools to be inserted and manipulated through the single port. Once the port is created, articulating instrument delivery tubes (IDTs) are inserted into the abdominal cavity and instruments are guided to the

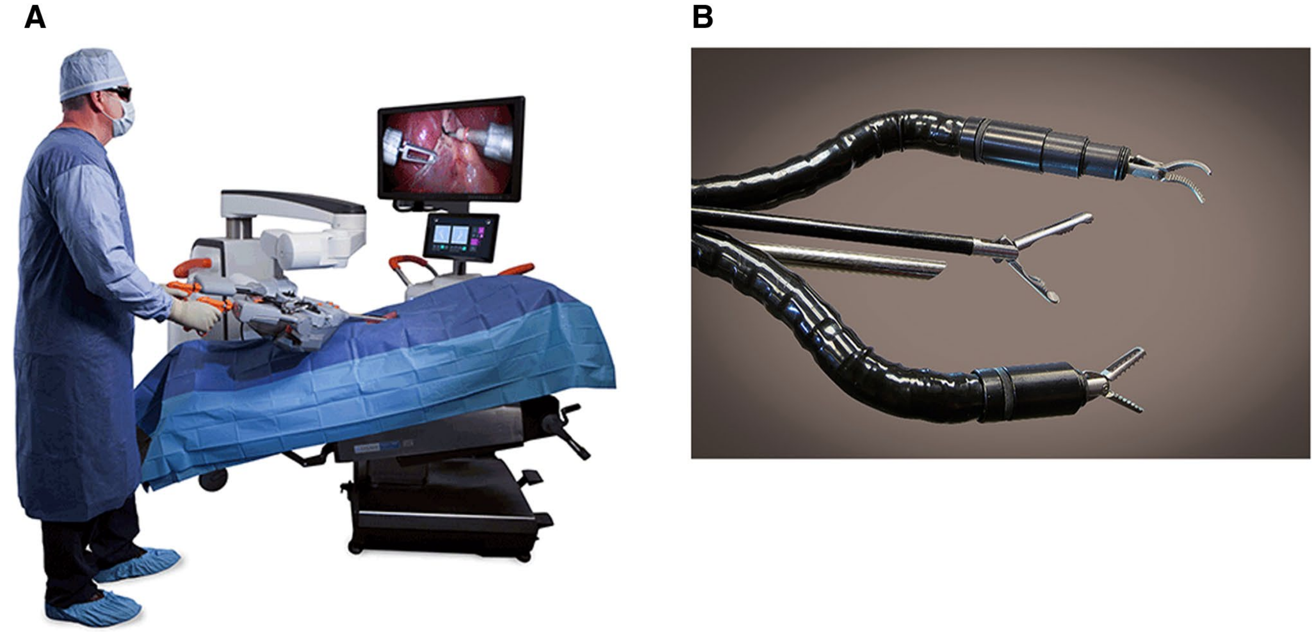

Fig. 12 **A** SurgiBot™ robotic system and **B** flexible instrumentation (TransEnterix, Durham, NC) [2]

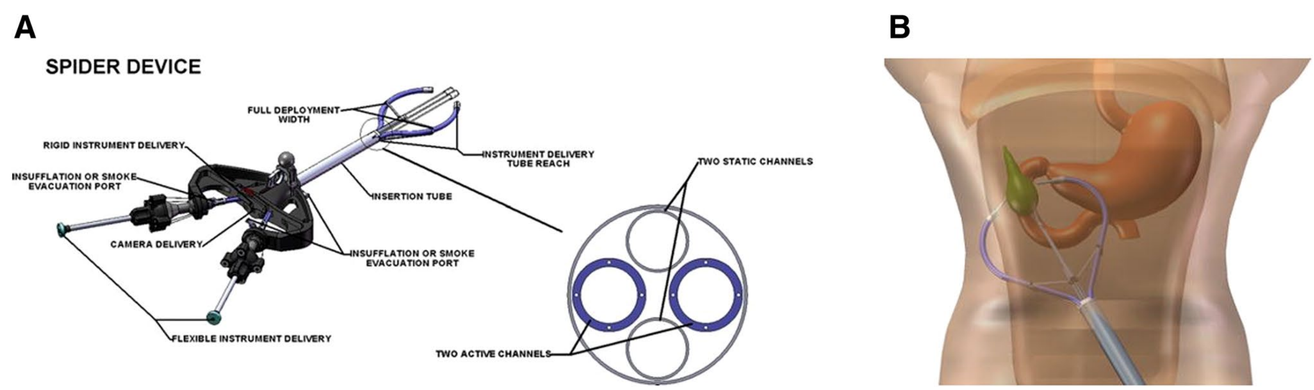

Fig. 13 **A** TransEnterix Single-Port Instrument Delivery Extended Research (SPIDER®) device, also showing a cross-sectional view of the delivery tube with four working channels. **B** SPIDER® in use for a laparoscopic cholecystectomy (TransEnterix, Durham, NC) [57]

appropriate location. As the tools are eased into the abdomen, a retractable sheath covering the distal end of the tube protects internal tissues. SPIDER maintains visualization of the operative field and instrument orientation (triangulation) similar to other current laparoscopic techniques. There are several advantages to this device, including simple retraction and true triangulation without added operating time, lower morbidity, improved cosmetic outcomes, and quicker recovery. Improved endomechanical vertebral arms provide increased strength for dissection and retraction. Additionally, the design incorporates true right and true left instrumentation, which eliminates 'crossed-arms' movement [6].

The design of SPIDER limits instrument size to 5 mm, which necessitates alternative options for procedures requiring larger, non-compatible instruments such as trocars. Endoscopic suturing was also shown to be challenging due to instrument design [58]. Additionally, smaller size ports (5 mm) often result in more trauma to the tissue than larger ports (10 mm) [57]. FDA approval was obtained in 2009. A sister technology to SurgiBot, both owned by TransEnterix, the SPIDER system was developed and sparsely used, leading to its merger into the SurgiBot platform.

Versius Robotic System

The Versius Robotic System (Cambridge Medical Robotics Ltd., Cambridge, UK; Fig. 14) is a lightweight modular robotic system designed for laparoscopic upper GI,

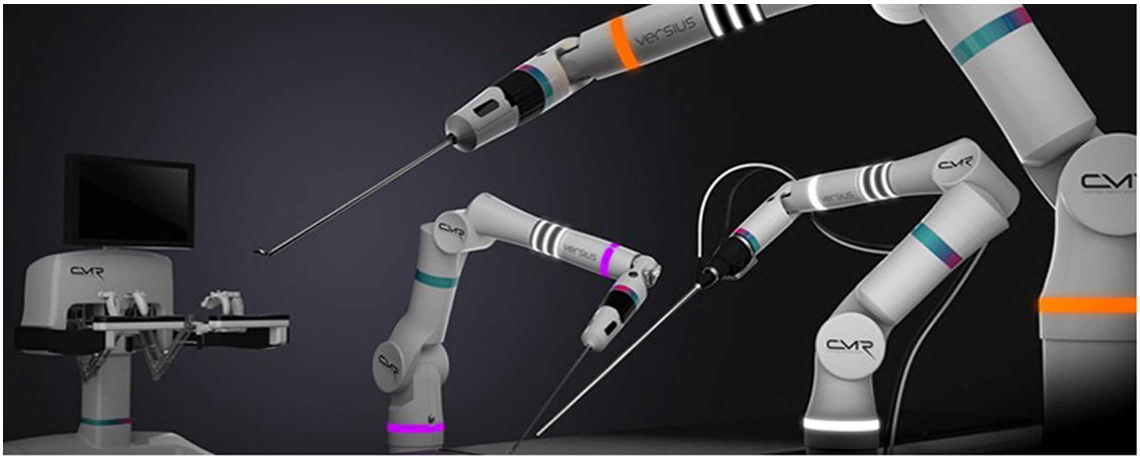

Fig. 14 Versius Robotic Surgery System (Cambridge Medical Robotics Ltd., Cambridge, UK) [60]

gynecological, colorectal, and renal surgeries. The modular design allows flexibility and versatility of positioning in the operating theater while providing numerous robotic arms connecting instruments such as graspers, scissors, electrocautery electrodes, and needle drivers [59].

The system is composed of an operator console and modular wristed robotic arms. The surgeon controls the robotic arms via joystick controllers at the console, while wearing HD–3D glasses and viewing a monitor. Haptic feedback from instrument to controller provides force feedback to the operator. Several variants of robotic arms using 5 mm instruments have been developed in order to reduce incision size [59].

Cadaveric trials held at The Evelyn Cambridge Surgical Training Centre have successfully shown the system's ability to perform electro-surgery, needle driving, suturing, and tissue manipulation. Europe's CE Mark and FDA approval are estimated for Early 2018 [59].

MASTER

The master and slave transluminal endoscopic robot (MASTER) (Nanyang Technological University and National University Health System; Fig. 15) is a multidimensional robotic device for NOTES [52]. The platform allows bimanual steering of two arms, provides dexterity, triangulation, haptic feedback to maintain spatial orientation, and a navigation system that allows a three-dimensional reconstruction that can be utilized to maneuver in real time [51].

Composed of a master console with a cable-driven flexible robotic slave, the device incorporates two end effectors, a monopolar electrocautery hook, and a grasper [5, 49, 52]

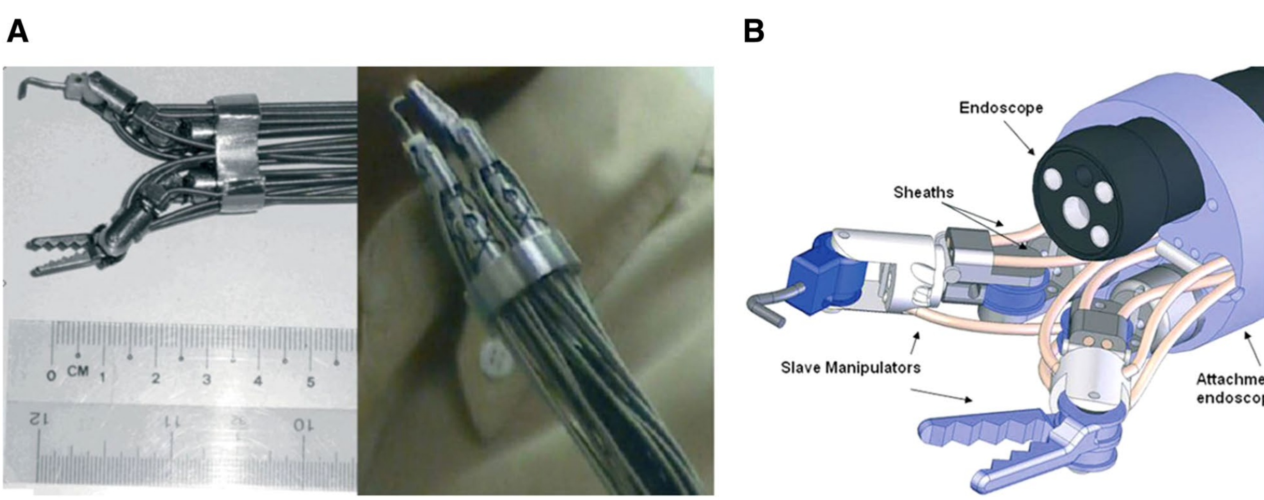

Fig. 15 MASTER; Nanyang Technological University. **A** The MASTER system has two cable-actuated robotic arms with fixed end effectors. **B** The system is shown attached to a conventional endoscope [52]

A full-time forceps operator guides the telechir (a robot arm under human control) through a master control device and actuator, while a second operator working in conjunction with the first is responsible for the use of an endoscope [52, 61]. The first operator is the surgeon, controlling the master interface slave manipulator, and executing the treatment. The endoscopist directs the endoscope to the desired location, and has control over suction and inflation. Cooperation between the two is required for the surgery [62]. Endoscopic vision and surgical navigation systems are viewed on digital monitors [62]. The flexible endoscope uses a tendon-sheath mechanism for actuation, and is capable of nine DOF.

Although non-linear backlash and hysteresis are intrinsic drawbacks of friction in the tendon-sheath actuation mechanism, the modality provides larger forces with a smaller size than alternative technologies [62]. The developer's future directions include improving automated movements, as well as enhancing haptic feedback [52]. MASTER has been validated clinically in performing endoscopic sub-mucosal dissections (ESD) treating early gastric neoplasia [62]. During publication, no information on FDA approval was available.

Verb surgical

Verb Surgical (Verb Surgical Inc., J&J/Alphabet, Mountain View, CA, USA) is a company formed through the collaboration of Johnson & Johnson's medical device company Ethicon Endo-Surgery, Getinge, and Alphabet's (Google) Verily Life Sciences [63]. The company became incorporated in August 2015 and aims to create a true surgical robot—a device that is not simply the extension of a surgeon [64]. A demonstration of the digitally enabled surgery platform prototype was delivered to collaboration partners in January 2017 [63].

The device incorporates advanced instrumentation, connectivity, data analytics, advanced robotics, advanced visualization, simulation, and machine learning [65]. One of Verb's main goals is to "democratize surgery" and increase information that the surgeon is given during a procedure [64]. The goal of Verb Surgical has been reported not to be the introduction of a new robotic surgical platform so much as the introduction of a new category of digital surgery [66]. Colloquially termed Surgery 4.0, Verb is attempting to create the successor to open, minimally invasive, and first-generation surgical robotic platforms, Surgeries 1.0, 2.0, and 3.0, respectively [66]. The prototype has been reported to combine robotics and data-driven machine learning in a way to reduce surgical costs and expand the use of such devices to a larger array of surgeons [65]. Several attempts to contact Verb Surgical regarding further dissemination of information regarding the platform were unsuccessful. Contacting the media department via electronic mail was met with an automatic reply confirming the correspondence, while suggesting that information is being kept strictly proprietary. Ironically, using the powerful Google search engine to elucidate contact information for further queries was unsuccessful.

Miniature in vivo robot (MIVR)

Virtual Incision, in collaboration with The Center for Advanced Surgical Technology (CAST) at the University of Nebraska Medical Center in Omaha, has developed a MIVR that can be used in a variety of robotic-assisted procedures (MIVR, Virtual Incision, CAST, University of Nebraska Medical Center, Omaha, Nebraska, USA; Fig. 16). The development of robotic tools that are miniaturized may be of great benefit to minimally invasive surgery [3]. The MIVR platform has been developed in order to significantly reduce size and can be maneuvered completely inside of the peritoneal cavity. Additionally, MIVR can be quickly repositioned to enable multiquadrant access in the abdomen [67]. The robot is composed of two arms, each with multiple joints. The forearm of each robotic arm allows interchangeable end effectors to be utilized for grasping and monopolar electro-cauterization. Miniaturized devices have the capability to improve laparoscopic surgery or even overcome many of the limitations of laparoscopy [68]. Reducing the size of robotic-assisted surgical platforms will increase the ease of use in the operating room due to a smaller footprint [17]. Depending on the procedure to be performed, multiple tools can be inserted into the peritoneum without any limitations from the size of the natural orifice [3].

One of the key technological advancements of the MIVR system is the miniaturization of robotic arms and the motors that drive them, which allows for a reduced footprint and greater access to the patient relative to conventionally sized robotic-assisted platforms [67]. While MIVR has end effectors similar to current robotic-assisted laparoscopic systems, novel technology has allowed the robot to compartmentalize all of its drive technology into the arms themselves, thereby eliminating the need for large motors and pulleys as seen in full-scale platforms [67]. The compact nature of MIVR allows it to be inserted through a single incision the size of a traditional colectomy extraction site [67].

In a study performed by Wortman et al., the MIVR robot successfully performed a robotic-assisted single-incision colectomy in a porcine model. In that trial, two arms and a camera were inserted and extracted via the same port, thereby serving as a true single-incision miniaturized robotic-assisted surgical system [67]. Additionally, in South America, initial feasibility and safety trials in humans have proven the system capable of both right and left colectomy [9]. Multiple surgeries were accomplished without any harm to the patient, and demonstrated the ability of the robot to dissect, ligate, and suture [9]. The continuing development

Fig. 16 Miniature in vivo robots. The Virtual Incision surgical robot is shown (Virtual Incision, Omaha, NE) [2]

of MIVR by Virtual Incision, a University of Nebraska Medical Center start-up company, is leading to the commercialization of the system. Additional iterations on the platform are planned, including small inexpensive robots for gallbladder removal, and a robotic-assisted hernia repair system. Virtual Incision is currently performing final design phase development and applying for 510 k FDA clearance for sale in the United States.

Einstein surgical robot

The Einstein surgical robot (Medtronic, Minneapolis, MN) is a platform currently under development by the Minimally Invasive Therapies Group (MITG) at Medtronic. The flexible system with robotic arms will implement parallel pathing of minimally invasive surgical instruments [59]. Initial uses will include bariatric, thoracic, colorectal, and urologic surgical procedures [59]. Average cost of procedure, relative to existing commercial platforms, was identified as prohibitive to system implementation. Therefore, design of the Einstein has focused on its utilization in an extensive array of procedures [59]. Einstein's development has been in conjunction with a variety of partnerships including Mazor, the German Aerospace Center (DLR), as well as the acquisition of the medical device manufacturer Covidien [59]. The timeline for FDA approval was not available, with India reported as the initial launch location [59]. A Medtronic external communications representative declined a permission request for the reuse of a figure depicting the Einstein Surgical Robot from Medtronic's 2016 Investor Day Pamphlet, therefore no image of the platform is provided here.

Discussion

The rising use of robots for assisting surgery has allowed the integration of modern technology in medicine. The digital robotic-assisted surgery platforms discussed here have spawned from a generation of designers who are comfortable with video game like interfaces and are able to implement heretofore unparalleled computing power and visualization modalities [69]. However, the quest to break through existing barriers in procedural capabilities is not new to our time. In his treatise on fistula, Hippocrates wrote of the earliest recorded tool for investigating body orifices: "…examining the ulcerated part of the bowel by means of the rectal speculum…" Millennia passed before the advent of endoscopy, which preceded electricity. Throughout time, technology has provided a platform on which to advance medical procedures: laparoscopy in 1910, robotic-assisted surgery in 1983, and the world's first in vivo miniaturized robotic surgery in 2016 [8, 70]. To date, the use of surgical robotic platforms for minimally invasive surgery has made considerable progress. Advancements in the field have allowed movement from open surgery to laparoscopic and other minimally invasive surgical procedures. This has led to an increase in the development of robotic laparoscopic systems. Available devices continue to reduce in size and become more procedure specific as technology becomes cheaper, smaller, and faster.

With each successful implementation of robotic technology in the operation room, the foundation for future systems is solidified. One independent research organization, involving over 50 participants in the market, forecasts that surgical robots will account for $20 Billion in annual revenue by 2021 [69]. With a growing footprint in the arsenal of options available to surgeons, it is possible that eventually all surgery will contain at least some robotic component representation. Additionally, with recent commercialization of partially and fully autonomous systems such as self-driving cars, public perception of and trust in artificial intelligence pertaining to matters of personal safety is likely to change rapidly [71]. Robotic surgical systems capable of automatic suturing, identifying tissue types, and performing autonomous procedures may follow in the wake of successful implementation of expanded automation in other industries. Furthermore, in August 2017 the Chinese artificial intelligence robot Xiaoyi developed by Tsinghua University scored 456 out of 600 points on China's medical licensing exam, proctored by the National Medical Examination Center. The passing score is 360 [72]. Although the development of autonomous surgical robotic technologies have not been widely reported, it seems prudent to expect them considering the historical relationship between emerging technology and its implementation in medicine. However, it will be necessary to address the cost per surgery, outcomes, and training involved along the way. Limiting costs to providers and insurers may prove to be a substantial hurdle in future development.

Studies to identify the feasibility of incorporating surgical robotic systems into existing practice have compared available technologies to conventional techniques. For instance, operative times and perioperative outcomes of a selected patient cohort undergoing Robotic-Assisted Laparoendoscopic Single-Site (R-LESS) surgery by a single physician were shown to be competitive with conventional techniques [73]. Although data to support the potential effectiveness of emerging systems will require time to generate, the prototypical da Vinci Surgical System has been demonstrated to safely and feasibly address robotic surgery challenges in multiple institutions [74]. Furthermore, complication rates in technically complex procedures have been shown to be comparable to open surgery, with the additional possibility of reduced recovery time [75].

The clinical need that robotic surgical technologies fulfill is largely dependent on, and determined by, the individual surgeon. Once initiated, implementation of new technologies into existing routines and standard operating procedures may encounter a constellation of possible ramifications, ranging from short learning curves to collaborative inter-professional resistance. Quantifying this process is difficult due to the evolving nature of the field and the rarity of reports comparing evidence-based outcomes across comparable datasets. One evaluation reporting on robotic versus laparoscopic procedures found that integrating surgical robotic technologies into practice was influenced by several factors including adequate training of all team members, operating room size parameters, and previous experience with robotic platforms [76]. Additionally, the timeline to integration endpoint is dependent on the procedure; the number of procedures completed to become proficient varies between operations. For instance, it has been shown that preparation with the da Vinci Surgical System leads to proficiency of basic skills with five repetitions, while 15–20 are necessary for more complicated skills [77]. Studies have also shown that once proficiency has been established for a particular operation, improvements in morbidity, mortality, and operative times are gained [77].

Generally speaking, the surgical robotic platforms described here market benefits over their open surgery contemporaries. However, in spite of increased adoption of robotic platforms in the operating suite, insufficient literature exists to concretely exemplify the superiority of these robotic systems over their conventional analogs. The need for additional research on robotic procedure patient outcomes is amplified by indications of potential bias in current reports, influenced by conflict of interest leading to positive conclusions [78]. However, retrospective database evaluative studies exist that have described longitudinal use of robotic systems that address the clinical need of physicians. For instance, a report on the use of robotic-assisted radical nephrectomy for renal mass over a 12-year ($n = 27{,}753$) span found no increased risk of negative postoperative outcomes compared to conventional procedures, although operating times and cost of procedure increased [79]. While the implementation and use of robotic-assisted surgery was found to increase 25.5% from 2003 to 2015, it was conceded that the increase may have been due to influences beyond large sample size evidence-based randomized studies, such as marketing efforts of system designers and the impetus to offer the most innovative technology [79]. However, additional studies have shown that the trend of conversion from open to robotic-assisted surgery is clear. Additionally, the overall growth in robotic-assisted procedures in surgical subspecialties may enable further conversion from open to robotic-assisted surgery [11].

Both patients and surgeons will likely benefit from more advanced surgical robots. Patients are expected see better outcomes and quicker recovery times, while surgeons will enjoy devices with increased dexterity and more compatible instruments. Additionally, with further advances in surgical robotics, it may be possible to perform procedures in isolated areas that are difficult to access. For instance, platforms that are operated teleremotely are being designed to allow the surgeon to be separated from the patient by great geographical or even planetary distances. However, the current landscape is full of challenges for the system developer, least of which is the process of obtaining FDA approval. The FDA clearance process requires surgeons to report events that led to halted surgeries or patient death. A denial can result in costly delays bringing products to market or send the developer back to the drawing board. Additionally, while there have been rapid advances in robotic systems, large gaps in technology still exist; although the cost of computing power has continued to decline, a corollary decline in available research funding has stung developers. Furthermore, certain technology applications require continued refinement if they are to meet the expectations of specialized physicians. For instance, haptic feedback devices, safety mechanisms, and instrument range of motion of instruments must be highly evolved and error free [80, 81].

The area of robotic-assisted surgeries is rapidly changing. Some of the technical information is proprietary and was not available at the time of this publication. There might be other companies awaiting FDA approval that we are not aware. Therefore, the list of robotic systems present in this article cannot be the complete list of all potential devices or companies that currently exist. In fact, we believe that this list will continue to grow with the advances of technology and improved outcomes for patients and surgeons.

In conclusion, emerging platforms for robotic-assisted surgical procedures are increasing in number and fueled by growth in the current market. Developers are rapidly implementing new technologies to improve on the capabilities of previously established systems. The upward trend of conversion from conventional to robotic-assisted surgery provides encouragement for the surgeon seeking to utilize robotic-assisted technology in their practice [11]. Although further studies are required to evaluate the strengths and weaknesses of robotic involvement in the operating suite, initial data have shown that robotic-assisted platforms are able to provide comparable results relative to conventional procedures.

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Compliance with ethical standards

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References

1. Kumar A, Yadav N, Singh S, Chauhan N (2016) Minimally invasive (endoscopic-computer assisted) surgery: technique and review. Ann Maxillofac Surg 6:159
2. Walker AS, Steele SR (2016) The future of robotic instruments in colon and rectal surgery, vol 27. Elsevier, Amsterdam, pp 144–149
3. Oleynikov D (2008) Robotic surgery. Surg Clin North Am 88:1121–1130. https://doi.org/10.1016/j.suc.2008.05.012
4. Rassweiler JJ, Teber D (2016) Advances in laparoscopic surgery in urology. Nat Rev Urol 13:387–399. https://doi.org/10.1038/nrurol.2016.70
5. Simorov A, Otte RS, Kopietz CM, Oleynikov D (2012) Review of surgical robotics user interface: what is the best way to control robotic surgery? Surg Endosc 26:2117–2125. https://doi.org/10.1007/s00464-012-2182-y
6. DACH Medical Group—English (2017). https://www.dach-medical-group.com/en. Accessed 20 Dec 2017
7. Rivera-Serrano CM, Johnson P, Zubiate B, Kuenzler R, Choset H, Zenati M, Tully S, Duvvuri U (2012) A transoral highly flexible robot. Laryngoscope 122:1067–1071
8. World's First Use of Miniaturized Robot in Human Surgery—Virtual Incision Corporation (2017). https://www.virtualincision.com/fim-surgery/. Accessed 20 Dec 2017
9. van den Bedem LJM (2010) Realization of a demonstrator slave for robotic minimally invasive surgery. Doctoral degree 22-09-2010; Department of Mechanical Engineering; Supervisors: M. Steinbuch and I.A.M.J. Broeders; Co-promotor: P.C.J.N. Rosielle; Eindhoven: Technische Universiteit Eindhoven. https://doi.org/10.6100/IR684835
10. Hanly EJ, Talamini MA (2004) Robotic abdominal surgery. Am J Surg 188:19–26
11. Armijo PR, Pagkratis S, Boilesen E, Tanner T, Oleynikov D (2017) Growth in robotic-assisted procedures is from conversion of laparoscopic procedures and not from open surgeons' conversion: a study of trends and costs. Surg Endosc. https://doi.org/10.1007/s00464-017-5908-z
12. Tsui C, Klein R, Garabrant M (2013) Minimally invasive surgery: national trends in adoption and future directions for hospital strategy. Surg Endosc 27:2253–2257. https://doi.org/10.1007/s00464-013-2973-9
13. Alli VV, Yang J, Xu J, Bates AT, Pryor AD, Talamini MA, Telem DA (2017) Nineteen-year trends in incidence and indications for laparoscopic cholecystectomy: the NY State experience. Surg Endosc 31:1651–1658. https://doi.org/10.1007/s00464-016-5154-9
14. Rodriguez-Sanjuan JC, Gomez-Ruiz M, Trugeda-Carrera S, Manuel-Palazuelos C, Lopez-Useros A, Gomez-Fleitas M (2016) Laparoscopic and robot-assisted laparoscopic digestive surgery: present and future directions. World J Gastroenterol 22:1975–2004. https://doi.org/10.3748/wjg.v22.i6.1975
15. Ghezzi TL, Corleta OC (2016) 30 Years of robotic surgery. World J Surg 40(10):1–8

16. Higgins RM, Frelich MJ, Bosler ME, Gould JC (2017) Cost analysis of robotic versus laparoscopic general surgery procedures. Surg Endosc 31:185–192. https://doi.org/10.1007/s00464-016-4954-2
17. Beasly RA (2012) Medical robots: current systems and research directions. J Robot 2012:1–14
18. Al-Ahmad A, Grossman JD, Wang PJ (2005) Early experience with a computerized robotically controlled catheter system. J Interv Card Electrophysiol 12:199–202. https://doi.org/10.1007/s10840-005-0325-y
19. Hansen Medical (2017). http://www.hansenmedical.com/us/en/why-robotics. Accessed 20 Dec 2017
20. Rafii-Tari H, Payne CJ, Yang GZ (2014) Current and emerging robot-assisted endovascular catheterization technologies: a review. Ann Biomed Eng 42:697–715. https://doi.org/10.1007/s10439-013-0946-8
21. Russo AD, Fassini G, Conti S, Casella M, Di Monaco A, Russo E, Riva S, Moltrasio M, Tundo F, De Martino G (2016) Analysis of catheter contact force during atrial fibrillation ablation using the robotic navigation system: results from a randomized study. J Interv Cardiac Electrophysiol 46:97–103
22. Hlivák P, Mlčochová H, Peichl P, ČIHÁK R, Wichterle D, Kautzner J (2011) Robotic navigation in catheter ablation for paroxysmal atrial fibrillation: midterm efficacy and predictors of postablation arrhythmia recurrences. J Cardiovasc Electrophysiol 22:534–540
23. Datino T, Arenal A, Pelliza M, Hernandez-Hernandez J, Atienza F, Gonzalez-Torrecilla E, Avila P, Bravo L, Fernandez-Aviles F (2014) Comparison of the safety and feasibility of arrhythmia ablation using the Amigo Robotic Remote Catheter System versus manual ablation. Am J Cardiol 113:827–831. https://doi.org/10.1016/j.amjcard.2013.11.030
24. Stolzenburg JU, Franz T, Kallidonis P, Minh D, Dietel A, Hicks J, Nicolaus M, Al-Aown A, Liatsikos E (2011) Comparison of the FreeHand(R) robotic camera holder with human assistants during endoscopic extraperitoneal radical prostatectomy. BJU Int 107:970–974. https://doi.org/10.1111/j.1464-410X.2010.09656.x
25. Sbaih M, Arulampalam TH, Motson RW (2016) Rate of skill acquisition in the use of a robotic laparoscope holder (FreeHand®). Minim Invasive Ther Allied Technol 25:196–202
26. Tran H (2011) Robotic single-port hernia surgery. JSLS 15:309–314. https://doi.org/10.4293/108680811X13125733356198
27. Groth S, Rex DK, Rosch T, Hoepffner N (2011) High cecal intubation rates with a new computer-assisted colonoscope: a feasibility study. Am J Gastroenterol 106:1075–1080. https://doi.org/10.1038/ajg.2011.52
28. Kurniawan N, Keuchel M (2017) Flexible gastro-intestinal endoscopy—clinical challenges and technical achievements. Comput Struct Biotechnol J 15:168–179
29. Sterile single-use endoscopy; invendo medical GmbH (2017). http://www.invendo-medical.com/. Accessed 20 Dec 2017
30. Remacle M, Prasad V, Lawson G, Plisson L, Bachy V, Van der Vorst S (2015) Transoral robotic surgery (TORS) with the Medrobotics Flex™ System: first surgical application on humans. Eur Arch Otorhinolaryngol 272:1451–1455
31. Schuler PJ, Duvvuri U, Friedrich DT, Rotter N, Scheithauer MO, Hoffmann TK (2015) First use of a computer-assisted operator-controlled flexible endoscope for transoral surgery. Laryngoscope 125:645–648
32. Funk E, Goldenberg D, Goyal N (2017) Demonstration of transoral robotic supraglottic laryngectomy and total laryngectomy in cadaveric specimens using the Medrobotics Flex System. Head Neck 39(6):1218–1225
33. Johnson PJ, Serrano CMR, Castro M, Kuenzler R, Choset H, Tully S, Duvvuri U (2013) Demonstration of transoral surgery in cadaveric specimens with the medrobotics flex system. Laryngoscope 123:1168–1172
34. Mattheis S, Hasskamp P, Holtmann L, Schafer C, Geisthoff U, Dominas N, Lang S (2017) Flex robotic system in transoral robotic surgery: the first 40 patients. Head Neck 39:471–475. https://doi.org/10.1002/hed.24611
35. Fanfani F, Monterossi G, Fagotti A, Rossitto C, Alletti SG, Costantini B, Gallotta V, Selvaggi L, Restaino S, Scambia G (2016) The new robotic TELELAP ALF-X in gynecological surgery: single-center experience. Surg Endosc 30:215–221
36. Fanfani F, Restaino S, Rossitto C, Alletti SG, Costantini B, Monterossi G, Cappuccio S, Perrone E, Scambia G (2016) Total laparoscopic (S-LPS) versus TELELAP ALF-X robotic-assisted hysterectomy: a case-control study. J Minim Invasive Gynecol 23:933–938
37. Rassweiler JJ, Autorino R, Klein J, Mottrie A, Goezen AS, Stolzenburg J, Rha KH, Schurr M, Kaouk J, Patel V (2017) Future of robotic surgery in urology. BJU Int 120(6):822–841
38. Stark M, Pomati S, D'Ambrosio A, Giraudi F, Gidaro S (2015) A new telesurgical platform–preliminary clinical results. Minim Invasive Ther Allied Technol 24:31–36
39. Spinelli A, David G, Gidaro S, Carvello M, Sacchi M, Montorsi M, Montroni I (2017) First experience in colorectal surgery with a new robotic platform with haptic feedback. Colorectal Dis. https://doi.org/10.1111/codi.13882
40. Miller NS (2017) Florida Hospital 1st in nation to use new robotic surgery system. Orlando Sentinel. http://www.orlandosentinel.com/health/os-florida-hospital-TransEnterix-robotic-surgery-20171114-story.html. Accessed 20 Dec 2017
41. Auris Surgical Robotics (2017) Auris indications for use statement and 510 k summary bronchscopy v4 052616 ra. http://www.accessdata.fda.gov/cdrh_docs/pdf15/k152319.pdf. Accessed 20 Dec 2017
42. Romo E, Bogusky J (2014) Auris Surgical Robotics Inc. Endoscopic device with helical lumen design. US Patent 20,150,164,594
43. Harris M (2016) First surgical robot from secretive startup Auris cleared for use. IEEE Spectr. https://spectrum.ieee.org/the-human-os/biomedical/devices/first-surgical-robot-from-secretive-startup-auris-cleared-for-use. Accessed 20 Dec 2017
44. Eickhoff A, van Dam J, Jakobs R, Kudis V, Hartmann D, Damian U, Weickert U, Schilling D, Riemann JF (2007) Computer-assisted colonoscopy (the NeoGuide Endoscopy System): results of the first human clinical trial ("PACE study"). Am J Gastroenterol 102:261–266
45. Gudeloglu A, Brahmbhatt J, Parekattil S (2014) Robotic microsurgery in male infertility and urology—taking robotics to the next level. Transl Androl Urol 3:102
46. Prendergast JM, Rentschler ME (2016) Towards autonomous motion control in minimally invasive robotic surgery. Expert Rev Med Devices 13:741–748
47. Henry B, Novarro G, Santo G (2017) Peering Behind The Veil of Secrecy In Surgical Robotics & 2016 Market Outlook
48. Hagn U, Konietschke R, Tobergte A, Nickl M, Jörg S, Kübler B, Passig G, Gröger M, Fröhlich F, Seibold U (2010) DLR MiroSurge: a versatile system for research in endoscopic telesurgery. Int J Comp Assist Radiol Surg 5:183–193
49. Konietschke R, Hagn U, Nickl M, Jorg S, Tobergte A, Passig G, Seibold U, Le-Tien L, Kubler B, Groger M, Frohlich F, Rink C, Albu-Schaffer A, Grebenstein M, Ortmaier T, Hirzinger G (2009) The DLR MiroSurge—A robotic system for surgery. Robotics and Automation, 2009 ICRA '09 IEEE International Conference on 1589–1590. https://doi.org/10.1109/ROBOT.2009.5152361
50. Tobergte A, Helmer P, Hagn U, Rouiller P, Thielmann S, Grange S, Albu-Schaffer A, Conti F, Hirzinger G (2011) The sigma.7

haptic interface for MiroSurge: a bi-manual surgical console, pp 3023–3029
51. Klibansky D, Rothstein RI (2012) Robotics in endoscopy. Curr Opin Gastroenterol 28:477–482. https://doi.org/10.1097/MOG.0b013e328356ac5e
52. Yeung BP, Gourlay T (2012) A technical review of flexible endoscopic multitasking platforms. Int J Surg 10:345–354. https://doi.org/10.1016/j.ijsu.2012.05.009
53. ViaCath diagnostic catheters (2016). https://www.biotronik.com/sixcms/media.php/136/ViaCath_EN.pdf. Accessed 20 Dec 2017
54. SPORT™ Surgical System (2017) Titan Medical Inc. http://www.titanmedicalinc.com/product/. Accessed 20 Dec 2017
55. SurgiBot (2017) http://www.transenterix.com/SurgiBot
56. Haskins O (2015) TransEnterix completes SurgiBot pre-clinical FDA work Bariatric News. http://www.bariatricnews.net/?q=node/1856. Accessed 20 Dec 2017
57. Pryor AD, Tushar JR, DiBernardo LR (2010) Single-port cholecystectomy with the TransEnterix SPIDER: simple and safe. Surg Endosc 24:917–923. https://doi.org/10.1007/s00464-009-0695-9
58. Haber G, Autorino R, Laydner H, Yang B, White MA, Hillyer S, Altunrende F, Khanna R, Spana G, Wahib I (2012) SPIDER surgical system for urologic procedures with laparoendoscopic single-site surgery: from initial laboratory experience to first clinical application. Eur Urol 61:415–422
59. Thibault M (2016) Finally, details on Medtronic's robotics platform. Medical Device Business. http://www.mddionline.com/blog/devicetalk/finally-details-medtronics-robotics-platform-06-08-16. Accessed 20 Dec 2017
60. CMR reveals versus robotic surgery system. (2016)
61. Kume K (2016) Flexible robotic endoscopy: current and original devices. Comp Assisted Surg 21:150–159
62. Lomanto D, Wijerathne S, Ho LKY, Phee LSJ (2015) Flexible endoscopic robot. Minim Invasive Ther Allied Technol 24:37–44
63. Verb surgical delivers digital surgery prototype demonstration to collaboration partners (2017). http://www.prnewswire.com/news-releases/verb-surgical-delivers-digital-surgery-prototype-demonstration-to-collaboration-partners-300397192.html. Accessed 20 Dec 2017
64. Simonite T (2016) The recipe for the perfect robot surgeon. https://www.technologyreview.com/s/602595/the-recipe-for-the-perfect-robot-surgeon/. MIT Technology Review 2017. Accessed 20 Dec 2017
65. Here's the Latest from Verb Surgical|MDDI Medical Device and Diagnostic Industry News Products and Suppliers (2017). http://www.mddionline.com/blog/devicetalk/heres-latest-verb-surgical-10-03-16. Accessed 20 Dec 2017
66. Khateeb OM (2016) Democratizing Surgery Part 1: What Verb surgical is creating. Robotics Buisness Review. https://www.linkedin.com/pulse/democratizing-surgery-how-verb-surgical-invented-new-category. Accessed 20 Dec 2017
67. Wortman TD (2011) Design, analysis, and testing of in vivo surgical robots. Department of Mechanical Engineering, University of Nebraska—Lincoln. http://digitalcommons.unl.edu/mechengdiss/28. Accessed 20 Dec 2017
68. Rentschler ME, Oleynikov D (2007) Recent in vivo surgical robot and mechanism developments. Surg Endosc 21:1477–1481. https://doi.org/10.1007/s00464-007-9338-1
69. Feussner H (2017) Surgery 4.0. In: Thuemmler C, Bai C (eds) Health 4.0: How Virtualization and Big Data are Revolutionizing healthcare. Springer, Cham, pp 91–107
70. Berci G, Forde K (2000) History of endoscopy. Surg Endosc 14:5–15
71. McMurray J, Strudwick G, Forchuk C, Morse A, Lachance J, Baskaran A, Allison L, Booth R (2017) The importance of trust in the adoption and use of intelligent assistive technology by older adults to support aging in place: scoping review protocol. JMIR Res Protoc 6:e218. https://doi.org/10.2196/resprot.8772
72. Yan A (2017) How a robot passed China's medical licensing exam: Machine shows capacity to learn, reason and make judgments but is not quite ready to go into solo practice, developers say. South China Morning Post. http://www.scmp.com/news/china/society/article/2120724/how-robot-passed-chinas-medical-licensing-exam. Accessed 20 Dec 2017
73. Moukarzel LA, Fader AN, Tanner EJ (2017) Feasibility of robotic-assisted laparoendoscopic single-site surgery in the gynecologic oncology setting. J Minim Invasive Gynecol 24:258–263
74. Tsukamoto S, Nishizawa Y, Ochiai H, Tsukada Y, Sasaki T, Shida D, Ito M, Kanemitsu Y (2017) Surgical outcomes of robot-assisted rectal cancer surgery using the da Vinci Surgical System: a multi-center pilot Phase II study. Jpn J Clin Oncol:1–6, https://doi.org/10.1093/jjco/hyx141
75. Galvez D, Sorber R, Javed AA, He J (2017) Technical considerations for the fully robotic pancreaticoduodenectomy. J Vis Surg 3:81. https://doi.org/10.21037/jovs.2017.05.08
76. Randell R, Honey S, Hindmarsh J, Alvarado N, Greenhalgh J, Pearman A, Long A, Cope A, Gill A, Gardner P, Kotze A, Wilkinson D, Jayne D, Croft J, Dowding D (2017) https://doi.org/10.3310/hsdr05200
77. Ozyurtkan MO, Kaba E, Toker A (2017) What happens while learning robotic lobectomy for lung cancer? J Vis Surg 3:27. https://doi.org/10.21037/jovs.2017.02.02
78. Criss CN, Gadepalli SK (2017) Sponsoring surgeons; an investigation on the influence of the da Vinci robot. Am J Surg, https://doi.org/10.1016/j.amjsurg.2017.08.017
79. Jeong IG, Khandwala YS, Kim JH, Han DH, Li S, Wang Y, Chang SL, Chung BI (2017) Association of robotic-assisted vs laparoscopic radical nephrectomy with perioperative outcomes and health Care costs, 2003 to 2015. JAMA 318:1561–1568. https://doi.org/10.1001/jama.2017.14586
80. Vasudevan V, Reusche R, Wallace H, Kaza S (2016) Clinical outcomes and cost–benefit analysis comparing laparoscopic and robotic colorectal surgeries. Surg Endosc 30:5490–5493
81. Waite KE, Herman MA, Doyle PJ (2016) Comparison of robotic versus laparoscopic transabdominal preperitoneal (TAPP) inguinal hernia repair. J Robot Surg 10:239–244