Robotic colorectal surgery
Current status and future developments

This manuscript considers the current state of robotic assisted surgery and, in particular, its application to colorectal disease. Further, we will consider the limitations of current technology and recent developments that may find application in the future.

Background
Laparoscopic surgery revolutionized general surgical and colorectal practice at the turn of the 21st century, effectively removing the morbidity associated with a large open abdominal wound. As with any new technology, it met with initial resistance driven by concerns about safety and effectiveness, which were most vocal in its application to malignant disease. In colorectal surgery, a responsible approach was generally taken, with the laparoscopic technique subjected to rigorous evaluation in large clinical trials prior to its widespread adoption [1, 2]. Despite an evidence base supporting its benefits for both patients and healthcare providers, the wider dissemination of laparoscopy, at least for major colorectal resection, has been slow. Penetration rates for laparoscopic colorectal cancer surgery vary, with the best rates of around 40% in countries with dedicated training programs [3]. The reasons for this are multifactorial, but undoubtedly the increased technical difficulty associated with laparoscopic surgery has played a major role. Laparoscopy removes the surgeon’s hand from the operative field, and in so doing takes away much of the tactile sensation and manual dexterity. In addition, 3-dimensional vision is replaced by a 2-dimensional image on a video-display unit, removing the depth of field perception that is critical to accurate surgical manipulation.

The application of robotic assistance to laparoscopic surgery was a logical extension of previous minimally invasive techniques.

The application of robotic assistance to laparoscopic surgery was a logical extension. With its 3-dimensional vision, stable camera platform, and intuitive, articulating instrumentation, the da Vinci® robotic system provided a platform to overcome many of the limitations of laparoscopy. But the da Vinci® system had its disadvantages, foremost being the capital cost of the equipment, but also the size and manoeuvrability of the surgical cart, an almost complete lack of tactile feedback, and limited application in multiquadrant abdominal surgery. Since its introduction in 1999, the da Vinci® system has undergone several refinements. The original system comprised a three-arm robot, with a camera arm and two operating arms. A fourth arm was added and the platform made smaller and lighter on the da Vinci® S platform. The current platform, the da Vinci® Si, incorporates high definition imaging with robotic arms and instruments to facilitate multi-quadrant operating, making it better adapted to colorectal surgery.

Current state
The evidence base
For colorectal surgery
The first publication describing the use of the da Vinci® system was by Weber et al. [4] in 2002, who demonstrated its potential in segmental colectomy for benign disease. Subsequent publications comprised a mixture of benign and malignant disease. The largest by D’Annibale et al. [5] reported 53 robotic assisted colectomies and compared outcomes with 53 laparoscopic resections. It concluded that robotic assisted surgery was as safe and effective as laparoscopic, was particularly useful in pelvic dissection, but that cost effectiveness needed further evaluation. Other reports confirmed the feasibility and safety of robotic assisted colectomy, with low rates of conversion, morbidity and mortality, but with increased operative times [6]. Only one study addressed the issue of hospital costs, comparing 30 robotic assisted with 27 standard laparoscopic cases and concluded that the total hospital cost was higher with the robot [7].

For tumour resection plus TME
The feasibility of robotics for total mesorectal excision (TME) rectal cancer resection was established by Pigazzi et al. [8] in a series of 6 low rectal cancers. A subsequent follow-up study of 39 rectal cancers treated prospectively by robotic assisted resection reported a zero rate of conversion with a mortality of 0% and morbidity of 12.8% [9]. The only randomized trial compared 18 patients assigned to robotic assisted resection with 18 patients assigned to standard laparoscopic resec-
Since 2006, there has been an explosion of robotic colorectal publications [11], the focus of which has been on rectal surgery, with particular attention to rectal cancer resection. In contrast, publications on robotic right colectomy have remained at a low, constant level. Several meta-analyses have been published. Antoniou et al. [11] looked at robotic-assisted surgery for both benign and malignant colonic and rectal disease, including 39 case series or non-randomized studies. They concluded that robotic right and left colectomies were associated with satisfactory rates for conversion (right 1.1%, left 3.8%) and operative morbidity (right 13.4%, left 15.1%). For anterior resection, the conversion rates to open surgery were exceptionally low (0.4%), with very respectable morbidity (9.7%).

Looking specifically at robotic rectal cancer resection, Oritz-Oshiro et al. [12] included 5 case-control studies comparing 486 patients, 203 of whom had undergone robotic and 283 laparoscopic rectal cancer resection. Of the factors investigated, the only parameter that showed a significantly favourable benefit for robotic surgery was conversion to open surgery (relative risk 0.31; 95% confidence interval 0.12–0.78). No difference was observed in oncological outcomes, hospital stay, or complications including anastomotic leak. Similar results were found in a meta-analysis by Memon et al. [13], who analyzed 7 studies, comprising 353 robotic assisted and 401 laparoscopic prostectomies, with particular focus on oncological outcomes. No difference between the robotic and laparoscopic groups was found for complications, circumferential resection margin involvement, distal resection margin, lymph node yield, or hospital stay. Once again, the only demonstrable difference was the significantly lower conversion rate associated with robotic rectal cancer resection.

### The conversion rate to open surgery was the only parameter with significant advantage in robotic assisted surgery

It seems logical to attribute the low conversion rate in robotic rectal resection to greater dexterity when operating in the pelvis, and this is certainly in keeping with the experience in radical prostatectomy. If this is true, then one might also expect increased surgical precision with the robot and perhaps also improved rates of autonomic nerve preservation. Postoperative bladder and sexual dysfunction is a well-recognized complication of both open and laparoscopic rectal surgery.

### Complication rates

There is some evidence that complication rates may actually be increased with the laparoscopic approach, particularly for low cancers [14]. Only one study has looked specifically at bladder and sexual dysfunction in robotic rectal surgery [15]. Kim et al. prospectively evaluated 69 patients undergoing either laparoscopic (n=39) or robotic (n=30) TME for cancer. Urogenital function was assessed by uroflowmetry, the international prostate symptom score and the international index of erectile function at baseline and 1, 3, 6, and 12 months following surgery. As expected there was deterioration in urinary and sexual function following surgery, but with return towards baseline levels being significantly quicker in the robotic group. A similar potential benefit in autonomic nerve preservation was found, although not statistically significant, in the meta-analysis performed by Scarponata et al. [16]. In terms of patient selection for robotic surgery, the authors suggest that a benefit may be found in males, obese patients, those receiving preoperative radiotherapy and for tumours of the distal two-thirds of the rectum; these are the same criteria that have been found to predict conversion rate in laparoscopic surgery [17].

### Advantages and disadvantages

Taken together, the above literature confirms that robotics can be safely and effectively applied to colorectal surgery. However, the only consistent benefit that emerges is the low conversion rate, particularly in rectal cancer surgery, with any conclusions about improved pelvic autonomic nerve preservation being too premature. The main criticism levelled at robotics is the cost, and with the lack of any convincing benefits in outcomes the healthcare economics are difficult to justify. But the area of surgical robotics continues to evolve and it is impossible to judge the future role of the robot as more capabilities are added and the robotic repertoire expands (e.g. fluorescence imaging). Further large-scale studies are needed—with rigorous data collection and evaluation—to enable us to arrive at a more informed opinion.

### ROLARR trial

In 2009 the UK Medical Research Council, through its Efficacy, Mechanisms, and Effectiveness Board (EME), funded the ROLARR trial, which aimed to evaluate the safety and efficacy of robotic as compared to laparoscopic surgery for rectal cancer and importantly incorporated patient report outcomes and health economics analysis [18]. By necessity, given the relatively small number of centres undertaking robotic rectal cancer surgery, the trial was international in reach, including centres across Europe, Asia, Australia and the USA. The trial aims to recruit 400 patients, randomized equally to either robotic assisted or laparoscopic surgery. The primary end-point is conversion to open surgery, based on the hypothesis that the robot facilitates laparoscopic rectal resection and this will be reflected in a greater proportion of completed procedures as compared to conventional laparoscopy. Other key primary endpoints include pathological assessment of the circumferential resection margin (CRM status) as a surrogate marker of adequacy of oncological resection and local recurrence rates at the 3-year follow-up. Secondary end-points include complication rates, quality of life, urogenital function and health economics evaluation. At the time of writing, ROLARR is recruiting well and...
The difficulty in evaluating a new technology is matching the process of evaluation with the pace of evolution of the technology. In the case of the da Vinci® system, the basic robotic platform has not changed since the S-generation was introduced in 2006 and is unlikely to change in the foreseeable future. However, Intuitive Surgical continue to innovate with the current platform and have been alert to developments in the surgical arena. This includes adaptation of the platform to include a facility for single incision laparoscopic surgery (SILS); the digital da Vinci® platform may be ideally suited to SILS application with its ability to switch operator controls to accommodate the reverse instrument manipulation necessary for SILS. Other potentially innovative developments include a fluorescent imaging capability, the Firefly® platform, and robotic stapling device. The Firefly® platform brings a whole new dimension to resectional colorectal surgery, through its ability to facilitate intraoperative vascular, lymph node and nerve identification. A fluorophore, indocyanine green (ICG), is administered intravenously and visualized by the robot’s laparoscopic capability to perform near infrared (NIR) imaging. The vasculature containing ICG fluoresces green under NIR imaging, readily distinguishing vessels from other tissues (Fig. 1a, b). In comparison, nerves fail to take up the ICG and are distinguished by their lack of green fluorescence. Similarly, submucosal injection in the vicinity of a mucosal lesion will highlight the draining lymphatic basin, potentially aiding assessment of radicality of resection in malignant disease. Intravascular dissemination of and therefore macroscopic ischaemia, with obvious application to the assessment of anastomotic viability. Although the technology is not limited to robotic application, it adds another dimension to the integrated capability of the robot.

ICG is visualized by the robot’s laparoscopic capability to perform near infrared imaging

Currently, similar technology is under evaluation in a randomised trial comparing ICG/NIR with white light laparoscopy in the prevention of anastomotic leak, with encouraging initial results [19]. In comparison, the development of a robotic stapler does not stimulate quite the same excitement, but nevertheless it is certainly an advancement on current laparoscopic stapling technology. The motor driven robotic stapler can achieve angles of flexion superior to its laparoscopic equivalents, which in combination with articulation in 360°, greatly facilitates stapling low in the pelvis. The stapler comes with integrated software that provides feedback to the surgeon regarding tissue compression and a fail-safe mechanism to prevent stapler firing in the event that too much tissue has been included into the stapler jaws. Other technology on the horizon includes a multi-arm robotic device for natural orifice and transluminal surgery (NOTES), which in the arena of colorectal surgery may find application transanal endoscopic microsurgery (TEMs) for rectal neoplasms.
With the introduction of bowel cancer screening programmes and the increasing detection of early rectal neoplasia, this technology is likely to become increasingly popular in the near future.

**Limitations**

Despite the technological advances offered by the da Vinci® system, it is not without its limitations and its critics. Free from any serious competition, Intuitive Surgical, Inc. (Sunnyvale, CA) have been unchallenged in the surgical robotics market place and as a monopoly have been able to demand high capital purchasing costs and maintenance contracts. This has helped to elevate robotic surgery to an elite status, which has been used in certain healthcare systems as a promotional tool. As a result, there is a tendency for patients to view robotic surgery as being better, irrespective of the lack of supportive evidence. In other surgical areas, most notably radical prostatectomy, the robot has enabled surgeons not familiar with the laparoscopic approach to undertake minimally invasive procedures with resulting improvement in outcomes.

In colorectal surgery, however, the starting point for robotics has been different. The majority of colorectal surgeons are familiar with laparoscopic surgery, and therefore the learning curve is that required to master the robot rather than to learn a new laparoscopic approach. Many colorectal surgeons argue that for most cases, particularly involving the colon, they can undertake surgery as effectively with conventional laparoscopy and therefore the added costs of the robot cannot be justified. Until such time as contrary data becomes available, this viewpoint is probably justified and will be difficult to argue against.

Even accepting the added costs of the da Vinci®, the system is not perfect for multi-quadrant abdominal surgery. The robotic cart is large and in combination with the rest of the system (digital stack and surgeon console), it takes up significant room in the operating theatre. Ideally, the system is best employed in a dedicated robotics theatre with a specially trained nursing team to operate it, although with care it can be transported between theatres as required. Intraoperative-ly, great care must be taken in setting up the robot and selecting port positions, to prevent collisions of the external robotic arms. Once the robot is docked it is impossible to move the patient's position on the operating table (e.g. head down tilt) to facilitate dissection, which can be a major disadvantage in certain procedures that span abdominal quadrants, such as low anterior resection. Although undocking manoeuvres are possible, they add unnecessary operative time.

The articulating instruments undoubtedly increase surgeon dexterity and help to improve surgical accuracy, but they lack any tactile feedback. Instead, the surgeon has to rely more heavily on visual clues to determine the nature of tissue–instrument interaction, which can predispose to iatrogenic tissue injury. An assistant experienced in robotic surgery is desirable, to anticipate robotic movements and undertake instrument changes. The assistant and the remaining operating team are paradoxically disadvantaged by the robot; the surgeon being remote at a console effectively isolates him from the rest of the team and clues from facial expressions and body language are not apparent to predict the surgeon's next moves.

**Next generations**

Although Intuitive Surgical, Inc. have a monopoly in the commercial arena, many research groups have been working on robotic surgical devices with varying success. For convenience, these devices can be classified into those systems that deploy the main robotic slave system ex-
ternal to the body cavity (extracorporeal) and those that have taken a different approach, attempting to deliver the robotic system into the body cavity (intracorporeal). Examples of such systems are presented below.

**Extracorporeal surgical systems**

The ARTEMIS system [20] was one of the first surgical telemanipulators to be developed, and comprised two slave manipulators and a guided endoscopic system controlled via a joystick, voice activation or an automated endoscopic tracking system. The surgeon’s workstation provided a 3D operative image, a graphical user interface and 3D graphical simulation using specially designed KISMET software. This ARTEMIS concept was advanced at the University of California with a surgical platform known as the Raven surgical system [21]. The Raven I utilized 2 portable robotic arms, each with 7 DoF (degrees of freedom), which could be remotely controlled via an Internet connection. The second-generation, Raven IV, incorporated 4 robotic arms with 2 cameras and allowed 2 surgeons at separate locations to interact with the operating platform site via teleportation.

The Institute for Robotics and Mechatronics at the German Aerospace Centre have attempted to address the lack of tactile feedback by incorporating haptics into its DLR Miro system ([22], [22]). The robot consists of a 7 DoF surgical manipulator with position and torque sensors that can be used as a single robotic arm or in combination as a multirobot platform (MicroSurge) [23].

By incorporating haptics into the DLR Miro system, the goal is to overcome the lack of tactile feedback.

The Amadeus robotic surgical system (Titan Medical, Inc., Canada), bears similarities to the da Vinci® system. It is promoted as a 4-armed robotic surgical platform with enhanced vision systems, force feedback and telecommunication features that enable long distance robotic surgery. There is little public information regarding the specifics of the system or how far it is from commercialization.

The University of Technology in Eindhoven are developing Sophie (Surgeon’s Operating Force-feedback Interface Eindhoven [24]). This master–slave platform consists of a remote operating workstation and a robotic base unit which is clamped onto the operating table and accommodates three 4 DoF manipulators, allowing for changes in patient position without the need to de-dock/re-dock the robot. A potential advantage is in the cost, which is expected to be considerably less expensive than the da Vinci® system.

SRI International were initially responsible for the robotic system which gave rise to the da Vinci®. Its M7 surgical system is a telemanipulation platform that incorporates stereoscopic imaging, telerobotics, sensory devices, video, speech recognition and telecommunication. In 2006 the system gained recognition when it performed the first robotic surgical demonstration under simulated zero gravity on board a NASA C9 aircraft, and a year later collaborated in a joint venture to perform remote surgical tasks over a distance of 1,500 miles [25]. SRI International are also developing the Trauma Pod, which aims to extract casualties from a battlefield, diagnose injuries and perform life-threatening surgery prior to transfer to hospital.

**Intracorporeal surgical systems**

One of the primary drivers for intracorporeal robots is to realize the potential of NOTES. Two distinct approaches have been taken: one approach is to retain a platform structure to provide stability and act as the base for robotic manipulators, the other is more radical and dispenses with any rigid fixation in favour of free roaming devices.

**Platform-based systems**

Several iterations of a dexterous, dual-armed intra-abdominal robot system have been developed at the University of Nebraska ([26, 27], Fig. 3a). This consists of three modules that are inserted into the abdominal cavity through a laparoscopic port, assembled and anchored outside the body using a clamping mechanism fixed onto the operating table. Each robot arm has 2 DoF and interchangeable end-effectors, which are controlled via a tether by two haptic interfaces. A similar approach is used for the “clinical platform” stream of the Araknas project, a large multicentre research project coordinated at Scuola Superiore Sant’ Anna (SSSA), Italy [28]. This consists of the dual-armed SPRINT robot that is inserted through a SILS umbilical port and positioned via an exter-
nal positioning mechanism. Each arm has 6 DoF, an interchangeable end-effector and is controlled by a haptic interface. Current prototypes demonstrate promise with the ability to generate appropriate tool tip forces (~5 N) at speeds comparable to the human hand.

The Insertable Robotic Effector Platform (IREP) aims to provide an advanced system for SILS procedures and uses a platform approach similar to the Araknas SPRINT system. The IREP system comprises a support column, with 3 DoF stereoscopic camera with light-source, and two 5 DoF ‘snake’ manipulators with graspers [29]. It uses an external actuation unit to power the system and minimize the size of its intracorporeal component.

Mobile systems

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Conclusion

Much progress has been made since the introduction of laparoscopic surgery in the early 1990s. Although laparoscopic surgery can be used in many operations with good effect, it has recognizable limitations. Robotic assistance offers the ability to compensate for these limitations, restoring the surgeon’s normal dexterity, vision and tactile sensation.

The da Vinci® system instinctively offers many advantages, but so far the clinical benefits have not been obvious and cost remains a major barrier to widespread implementation and utilization. The fact that it reduces the need to convert to open surgery is perhaps testimony to its ability to facilitate laparoscopic surgery.

As robotic systems continue to evolve and their capabilities expand, it is possible that clinical benefits will begin to emerge. The future of robotic surgical systems, however, is exciting with many innovative platforms and mobile devices being developed that have the potential to radically change our surgical capabilities.

Conflict of interest. The corresponding author states that there are no conflicts of interest.

References


