ROBOTICS IN SURGERY – PAST, PRESENT AND FUTURE

Rajesh Aggarwal and **Ara Darzi**
Department of Biosurgery and Surgical Technology, Imperial College London, UK

Guang-Zhong Yang
Royal Society/Wolfson Medical Image Computing Laboratory, UK

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Contents

1. Introduction

The introduction of minimally invasive techniques to general surgery has been described as 'the most dramatic change in surgery since the introduction of anaesthesia'[1]. This has led to many procedures such as gallbladder removal and acid reflux procedures (Nissen fundoplication) being performed almost exclusively by the keyhole or laparoscopic approach [2,3]. Reasons for this paradigm shift are the benefits to patients and society in terms of decreased post-operative pain, a shorter hospital stay and a quicker return to daily activities[4-8].

These have motivated further attempts in extending the scope of laparoscopic surgery to other more complex operations. An example is the development of laparoscopic bowel, or colorectal surgery, with the expectation that patients will reap benefits similar to those involving simpler procedures. However, laparoscopic large bowel resection significantly extends the technical demands of the operating surgeon and can lead to a greater number of complications during the learning curve[9]. The expected benefits for patients undergoing complex laparoscopic surgery may therefore be less obvious when compared to those having simpler laparoscopic procedures.

Attempts have been made to address this issue with the introduction of hand-assisted laparoscopic surgery - a hybrid between laparoscopic and open surgery [10]. The surgeon places one hand into the abdomen through a 6-8cm incision, and thus can use traditional open surgical skills to operate, but through an incision of reduced, rather than minimal, size. In practice, the ideal situation would be a system that enables surgeons to operate using their traditional open surgical skills, whilst still maintaining the use of minimal access techniques. This is the basis of master-slave surgical robots, which can not only make complex laparoscopic procedures ergonomically easier to perform [11], but also further extend the scope of laparoscopy to new areas such as cardiac surgery[12].

2. Limitations of Laparoscopic Surgery

The advantages of laparoscopic surgery are well established and numerous studies have been performed comparing patient outcomes of open and laparoscopic cholecystectomy, fundoplication and groin hernia repair, all of them favouring the minimally invasive approach [13-16]. However, laparoscopic operations are initially difficult to perform and are only superior to the open approach once the learning curve of the operating surgeon has been taken into account.

Reasons for the difficulty in performing laparoscopic procedures are due to the extra motor and perceptual skills required and many of them are counterintuitive [17]. For example, in laparoscopic surgery, a surgeon must operate whilst using instruments which are over 12 inches long, leading to exaggeration of hand tremor and a decrease in the sense of touch. The instruments also have fewer degrees of freedom than the human wrist and hand and simple tasks such as suturing and tying knots are more significantly complex. This is exacerbated by the fulcrum effect, whereby movements of the instrument tips are opposite to those of the surgeon’s hands. This is akin to using chopsticks rather than standard cutlery, which is further hampered by operating whilst viewing a two-dimensional screen away from the normal eye-hand-target axis.

In laparoscopic surgery, learning to master these limitations takes time and many surgeons are hindered by the longer operating times and increased risk of complication when performing complex procedures such as colectomy. For this reason, only a few surgeons perform complex laparoscopic surgery regularly. The main motivation of developing robotic assisted laparoscopic surgery is to address the reduced dexterity and impaired visual control of laparoscopic surgery to ensure the safety, as well as the consistency of complex laparoscopic procedures.

3. The Development of Robotic Systems in Surgery

The first robot used in surgery was developed by Kwoh et al. in 1985, with the aim of improving the accuracy of a neurosurgical biopsy [18]. Further modification by Davies at al. in London in 1998 led to the development of Probot, a robot designed for transurethral (through the penis) resection of the prostate gland [19]. However, the first robotic device to be approved by the Food and Drug Administration (FDA) of the United States for clinical use was RoboDoc (Integrated Surgical Systems, Inc., Sacramento, CA, USA), a system designed to machine the femur (or thigh bone) with greater precision during hip replacement surgery [20].

The first robot approved for clinical use in the abdomen was the Automated Endoscope System for Optimal Positioning (AESOP) (Computer Motion Inc., Goleta, CA, USA). This consists of a single robotic arm which holds the camera during laparoscopic procedures. Control is achieved by pressing a foot switch or hand button and more recently through the use of a voice recognition system. Its design enables a surgeon to be in direct control of the surgical field of view, independent of the skills of the operating assistant who normally directs the camera. Studies have shown AESOP to be an adequate replacement for a human camera holder, allowing surgeons to perform some procedures without the need for an assistant [21]. This has led to the development of similar systems such as the FIPS Endoarm [22] (Karl Storz Endoscope GmbH, Tuttlingen, Germany) and Endoassist [23] (Armstrong Healthcare, High Wycombe, England), the latter moving in synchrony with the surgeon's head movements.

Figure 1. *The Da Vinci robotic system (*Reproduced with kind permission from Intuitive Surgical, Mountain View, CA, USA'*).*

For providing intuitive instrument control and enhanced dexterity, it was not until the early 1990s that a team from the National Air and Space Administration (NASA) proposed the concept of master-slave based tele-surgery, i.e. a virtual image of the operative field is projected to a remote site and the surgeon performs the procedure without actually seeing the patient. Together with researchers from the Stanford Research Institute (SRI), a system was developed for open surgery which gave the surgeon the sense of operating directly on the patient, whilst on the other side of the room. This was the birth of the first master-slave telemanipulator, later to be known as da Vinci (Intuitive Surgical, Mountain View, CA, USA), as shown in Figure 1 above. Within a year, Computer Motion had developed the AESOP system (Figure 2) into a telemanipulator known as Zeus (Computer Motion Inc., Goleta, CA, USA. Both machines have been approved for use in abdominal surgery by the FDA, and share a number of similarities.

Figure 2. *The Zeus robotic system and master unit (*Reproduced with kind permission from Intuitive Surgical, Mountain View, CA, USA'*).*

Each system consists of three separate parts: the surgeons console, a video stack system and the robotic arms. The console is a non-sterile area where the surgeon sits and controls the movements of the robotic arms, which are placed over the operating table. There are three arms, two for instruments and one for the camera. The console and robotic arms are connected by the video stack which contains camera and video equipment. However, there are also some differences between the two systems in terms of robotic arm and instrument design, as well as 3D viewing setup and motion scaling for tremor removal.

4. The Impact of Robotic Systems in Surgery

Improved visualisation and greater dexterity are two major features of robotic assisted laparoscopic surgery. The first procedure to be performed using a master-slave robot was by Cadiere et al [21] in March 1997, using a prototype da Vinci to complete laparoscopic cholecystectomy (gallbladder removal). They followed this with reports of master-slave robotic laparoscopic gastric bypass (a procedure for morbid obesity which attaches the stomach to the small bowel) [24], Nissen fundoplication (for acid reflux disease) [25] and fallopian tube reanastomosis [26]. A paper by the same group published in 2001 detailing 146 cases of robotic laparoscopic surgery concluded it to be feasible and especially useful for intra-abdominal microsurgery or for manipulations in very small spaces [27]. They reported no robot related deaths. Similar results have been published by Marescaux et al [26]. in a prospective study of 25 master-slave robotic laparoscopic cholecystectomies – 24 were performed successfully and one was converted to a traditional laparoscopic cholecystectomy. Again, the robotic procedure was found to be safe and feasible.

Since November 2000, our centre has performed over 200 procedures using the da Vinci master-slave robot and has recently reported the results of complex procedures such as Heller’s cardiomyotomy (for oesophageal narrowing) [28], adrenal gland excision [29] and rectopexy (a procedure for bowel incontinence) [30]. All procedures were completed successfully with the robot, without major complication or death. Mean operating time and hospital stay were comparable to traditional laparoscopic procedures. However, patient and machine set-up time took longer than in standard laparoscopic surgery.

Proponents have shown that it is entirely feasible to perform master-slave robotic laparoscopic surgery, but is the added expense justifiable? Once the robot has been positioned and the instruments are within the abdomen, the operation performed is the same as in traditional laparoscopic surgery. Hence, there may be no advantages conferred to the patient by having a robotic, rather than a standard laparoscopic approach.

However, the improved dexterity and better visualisation afforded by the robot may enable more accurate procedures to be performed. For example, in laparoscopic rectopexy (hitching up of the large bowel to the base of the spine to treat incontinence) it may be possible to reduce the complication of pelvic nerve injury and in Heller’s cardiomyotomy the incidence of oesophageal perforation may decrease. Our Department has also shown experimentally that the learning curve for robotic surgery is shorter than for laparoscopic surgery when performing a complex task such as laparoscopic suturing and knot tying[11]. This can not only reduce the time taken to achieve expert levels of skill, but also reduce the number of complications occurring at the expense of the learning curve.

5. Robotics for Gastrointestinal Surgery

Thus far, many centres have applied the da Vinci™ system to colorectal or large bowel surgery, to establish whether minimally invasive bowel resections can be achieved with greater technical ease. There are a small number of series demonstrating the feasibility of bowel resections ranging from right-sided colonic resections to *en masse* excisions of rectum and anus [31-35].

Weber et al. were the first to publish their experiences with master-slave robotic-assisted resections, performing one left-sided and one right-sided colonic bowel resection, both for benign disease [36]. The robotic arms were used to mobilise the bowel, while division of the attachments to the fat and restoration of bowel continuity were completed by traditional laparoscopic techniques. The average operative time was 50% longer than traditional laparoscopic resections but the authors felt that this was greatly due to their inexperience with this new technology. Subjectively, the surgeons felt the robot addressed many of the shortcomings of traditional laparoscopic colectomy making dissection easier. However, they did note a number of limitations whist using the systems. Firstly, whilst performing the right-sided operation it was necessary to disengage the robot in order to reposition the patient from Trendelenburg's (head down) to reverse Trendelenburg's (head up) position. This is relatively time consuming and if required many times during a procedure, would add considerably to the overall operative time. Mobilisation of the part of the large bowel attached to the spleen, i.e. the splenic flexure, during the left sided excision also had to be completed with traditional laparoscopic instruments, as the robotic instruments are too short. The greatest limitation with the da Vinci system, however, was the lack of tactile or force feedback, which in less experienced hands could lead to inadvertent damage to delicate tissues such as the bowel wall.

A more recent study compared 6 master-slave robotic colorectal cases with matched laparoscopic equivalent cases to establish whether a benefit of this new technique could be demonstrated [32]. The cases included 2 right sided colonic resections, 3 left sided resections and 1 rectopexy. The surgeons utilised the robot in a similar manner to Weber et al., performing only the colorectal dissection before completing the procedure with more conventional laparoscopic techniques [36] . End points measured were operative time, patient blood loss, hospital stay and cost. They reported a significantly longer 'incision to extubation ('end of anaesthesia') time' for the robotic-assisted cases (165 minutes) as compared to laparoscopic cases (108 minutes). There were no significant differences in blood loss, hospital stay or cost, although the latter did not include the capital expenditure on the robot. The authors commented that the present generation of robots requires repositioning to facilitate accessing multiple sites within the abdomen for colorectal surgery and the resultant increase in operative time cancels any benefits of using this technology for colorectal surgery.

Both of the above studies have largely concentrated on the use of the master-slave robot to perform the dissection for colonic procedures, which requires access to a large proportion of the abdominal cavity. Rectal dissection within the pelvis involves operating in much more limited field. This operative field is more analogous to operating in the thoracic or chest cavity, the role for which da Vinci™ was originally designed. The surgeon's ability to perform a nerve-sparing excision of the rectum could be enhanced by the unprecedented views into the pelvis provided by the 3-D image and improved dexterity from EndoWrists instrumentation [37].

The largest series to date of robotic rectal surgery only consists of 8 cases, made up of 6 left sided colonic and rectal resections and 2 resections of rectum and anus [33]. The mean operative times were longer than would be expected for conventional laparoscopic resections. However, the surgeon chose to complete the entire colonic dissection with the assistance of the robot, which entailed repositioning of the robot during the procedure. Our centre has suggested performing only the rectal dissection with da Vinci, completing the left colonic dissection by conventional laparoscopic methods. This avoids manoeuvring of the slave platform whist the patient is asleep [37].

Suture rectopexy is an operation whereby the rectum is hitched up onto the sacrum (or lower spine) and carried out for bowel incontinence. This can be performed entirely with the da Vinci system remaining in one anatomical location. In our series of 6 robotic-assisted rectopexies, we reported similar results to conventional laparoscopy. Subjectively it was felt the procedure was easier to master using the da Vinci as compared to completing the dissection with traditional laparoscopic instruments [38]. Vibert et al. have used da Vinci to suture an intra-abdominal colorectal anastomosis [35]. The robot allowed a continuous, multilayered anastomosis (or join) to be performed in confined operative field of the pelvis. Although interesting, it is unlikely that suture anastomosis will have a significant role to play now that stapled anastomosis are well established in colorectal surgery.

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Biographical Sketches

Rajesh Aggarwal PhD MA (Cantab) MBBS MRCS Eng

Rajesh Aggarwal began his medical training at Selwyn College, Cambridge University and completed clinical studies at The Royal Free Hospital School of Medicine, London, graduating with Honours. Subsequently he has completed surgical training in London teaching hospitals, and a PhD thesis at Imperial College London entitled ‘A Proficiency-Based Technical Skills Curriculum for Laparoscopic Surgery’. His work has been published in over 80 peer-reviewed papers, including Annals of Surgery, the British Medical Journal and New England Journal of Medicine. Dissemination of research is actively pursued through membership of committees directed by the Department of Health, the Royal College of Surgeons of England, the European Association of Endoscopic Surgeons and the Society of American Gastrointestinal Endoscopic Surgeons, together with the delivery of presentations to a number of audiences worldwide.

Professor Darzi studied medicine in Ireland and qualified from the Royal College of Surgeons. He obtained his fellowship in Surgery from the Royal College of Surgeons in Ireland and a M.D. degree from Trinity College, Dublin. He was subsequently granted the fellowships of the Royal College of Surgeons of England, The American College of Surgeons, the Royal College of Surgeons and Physicians of Glasgow and of the Royal College of Surgeons of Edinburgh. More recently he was awarded fellowship of the Academy of Medical Sciences and City and Guilds of London Institute and an honorary fellowship of the Royal Academy of Engineering. Professor Darzi was knighted by the Queen as a Knight Commander of the most excellent Order of the British Empire (KBE) in December 2002.

Currently Professor Darzi holds the Chair of Surgery Imperial College London where he is head of the Division of Surgery, Oncology, Reproductive Biology and Anaesthetics. He is an Honorary Consultant Surgeon at St. Mary's Hospital NHS Trust. He holds the Paul Hamlyn Chair of Surgery at the Royal Marsden Hospital. He held the office of the Tutor in Minimal Access Surgery at the Royal College of Surgeons in England where he set the national guidelines in education and training in Minimal Access Surgery. He was also a Council member of the Association of Coloproctologist of Great Britain and Ireland, The Association of Endoscopic Surgeons of Great Britain and Ireland, and the Society of Minimal Invasive Therapy.

Guang-Zhong Yang received his B.Sc. in Electrical Engineering from Shanghai Jiao Tong University, and Ph.D. in Computer Science from Imperial College, London. He served as a senior and then the principal scientist of the Cardiovascular Magnetic Resonance (CMR) Unit, Royal Brompton Hospital before rejoining Imperial College in April 1999. He is now the head of the Visual Information Processing (VIP) research group at the Department of Computing, and his current research focuses on Computational Vision, Image Processing, Perceptual Intelligence, Visual Simulation, and Biomedical Imaging Systems. Dr Yang received the I. I. Rabi Award in 1996 from the International Society for Magnetic Resonance in Medicine (ISMRM) for his work on Cardiovascular Magnetic Resonance Flow Imaging, and he currently serves as the Chairman of IEEE UK/RI Engineering in Medicine and Biology.