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Robotic urological surgery

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SUMMARY
Robotic technology has been used in urological surgery since the late 1980's with the invention of robotic endoscopic prostate surgery. The major technological landmark has been the widespread introduction of the da Vinci master-slave manipulator which is now used in up to 60% of radical prostatectomy operations in the USA. These machines offer a number of tools to facilitate laparoscopic surgery though they require both a human console operator and a surgical team to connect the device to laparoscopic ports in the patient's abdomen. We outline the improved outcomes and future development of prostatectomy, cystectomy and pyeloplasty associated with robotic technology.

KEYWORDS: Robotics; Radical prostatectomy; Cystectomy; Pyeloplasty

Introduction

Robotic urological surgery started in Guy's in the late 1980's as a collaborative project with the mechanical engineering department at Imperial College. This was in the form of a TURP frame called the PROBOT which could resect an enlarged benign prostate under ultrasound guidance without any interference from the surgeon.[1] Solo robotic surgery using voice-controlled camera holders and retractors was subsequently developed at The Johns Hopkins Hospital in Baltimore. Soon after, the first randomised transatlantic telerobotic trial of percutaneous nephrolithotomy was conducted between Guy's and Hopkins. It showed that while the robotic arm was slightly slower than a human hand it was significantly more accurate at inserting needles into the kidney remotely.[2] This trial was given the acronym STAR TRAK (**S**ystematic **T**rans-**A**tlantic **R**andomised **T**ele**r**obotic **A**ccess to the **K**idney).

Although the initial drive to develop active systems such as the PROBOT which could operate without human control held much promise, the complexity of many surgical tasks including pelvic surgery coupled with a relative lack of imaging or ultrasound control systems which could accurately direct the necessary instruments meant that much of the next phase of robotic development was centred on master–slave devices where a human operator directed a robot either with voice or with mechanical commands. Further details of the history of surgical robots and their introduction into the field of urology may be found in recent reviews.[3–5]

Laparoscopic urology advanced initially without the help of robotic assistance, but subsequent devices including the voice-activated robotic laparoscopic camera holder marketed as the automated endoscopic system for optimal positioning (AESOP) allowed the laparoscopic urologist to reduce the number of human assistants required for the procedure. The current state-of-the-art computer-assisted robotic tool is the da Vinci SHD (Fig. 1) from Intuitive Surgical. The concept behind this came from experiments by the U.S. army and the Green Telepresence system. The da Vinci is a master–slave device with magnified 3D vision and tremor-free endowrist instruments that allows surgeons to transfer their wrist and finger movements in a precise, intuitive fashion. While the da Vinci system was initially designed for general surgery in the military setting, it is in urology where robotic surgery has become most established. These technologies are increasingly popular in cardiac, gastrointestinal, gynaecologic, paediatric and ENT surgery. The commonest surgical procedure with this system is robot-assisted radical prostatectomy (RARP), particularly in the United States where there are currently more than 550 da Vinci robotic systems in operation (Fig. 2). The United Kingdom has started to follow this trend, with the number of da Vinci machines increasing from 1 to 12 between 2003 and the present day. While RARP constituted only 10% of the total volume of radical prostatectomy performed 2 years ago, it has increased to more than 60% in 2008–2009. This paper will summarise the current status of RARP and the other main urological procedures – cystectomy, pyeloplasty and partial nephrectomy – and provide an overview of further developments which may become implemented in future robotic tools.

Robot-assisted Radical Prostatectomy

The procedure of radical prostatectomy was challenging in open surgery for a number of reasons. The location of the prostate within the pelvis is relatively inaccessible as in men the pelvic inlet (space inside the pelvis) is narrow. Combined with this, the prostate is closely associated with other structures including the bladder (above), the cavernosal nerves (lateral to the prostate), the rectum (posteriorly) and the urethra. These structures require preservation. The bladder and urethra are reconstructed after removal of the prostate to allow normal function to be achieved. In open surgery, bleeding from the dorsal vein complex was often problematic and resulted in potentially life-threatening

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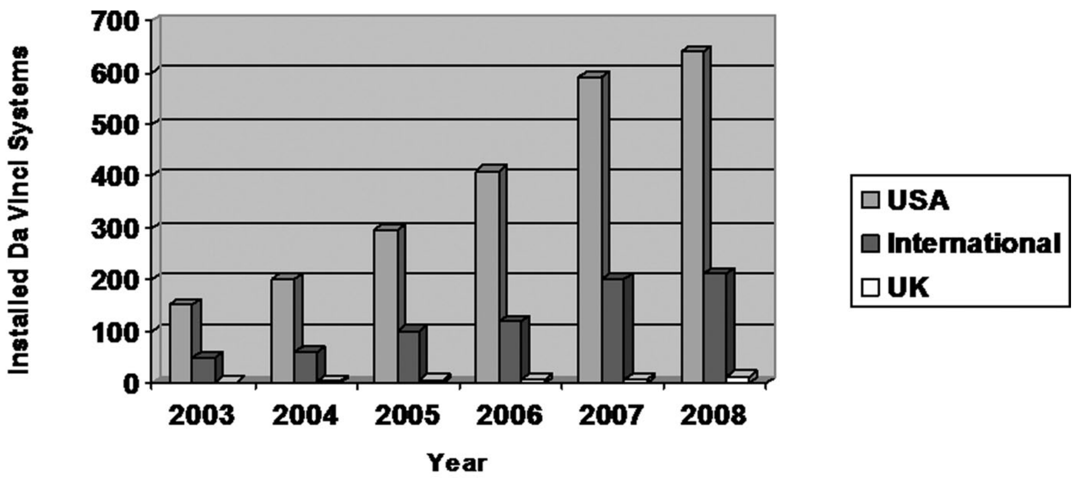
Fig. 1. Components to the da Vinci SHD system: (from left to right) console, patient side cart, stack system. (Courtesy of Intuitive Surgical).

haemorrhage. In laparoscopic and robotic procedures this is reduced as a result of the pressure (usually 10–15 mmHg) used to generate the pneumo-peritoneum. The main generally acknowledged advantage of laparoscopic and robotic procedures versus open surgery is a much decreased blood loss with avoidance of the need for blood transfusion.

However, laparoscopic radical prostatectomy (LRP) has some limitations due to the difficulties in manipulation of instruments that have only 4 degrees of freedom. This presents challenges in the extirpative phase when the instruments are used for cutting (usually scissors and/or monopolar or bipolar diathermy) and control of bleeding (clipping instruments, diathermy or other energy sources such as the harmonic scalpel) and in the reconstructive phase where sutures are used to re-attach the urethra to the bladder.

The da Vinci robotic surgery tool has advantages due to the presence of endowristed instruments. These allow the various manipulative and extirpative devices to be manipulated with 7 degrees of freedom due to the presence of the 'endowrists' in the design of the instruments as illustrated in Fig. 3. This allows manipulation of the instruments into small spaces without loss of the intuitive (to the human operator)



Installation Year	2003	2004	2005	2006	2007	2008
Devices Installed in the UK	1	2	5	6	7	12

Fig. 2. This chart shows the steady increase in the total installation of da Vinci systems within the United States, internationally and in the United Kingdom. (Courtesy of Intuitive Surgical).

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Fig. 3. The instruments used by the da Vinci system have endowrists which allow 7 degrees of freedom in manipulating the instrument. (Courtesy of Intuitive Surgical).

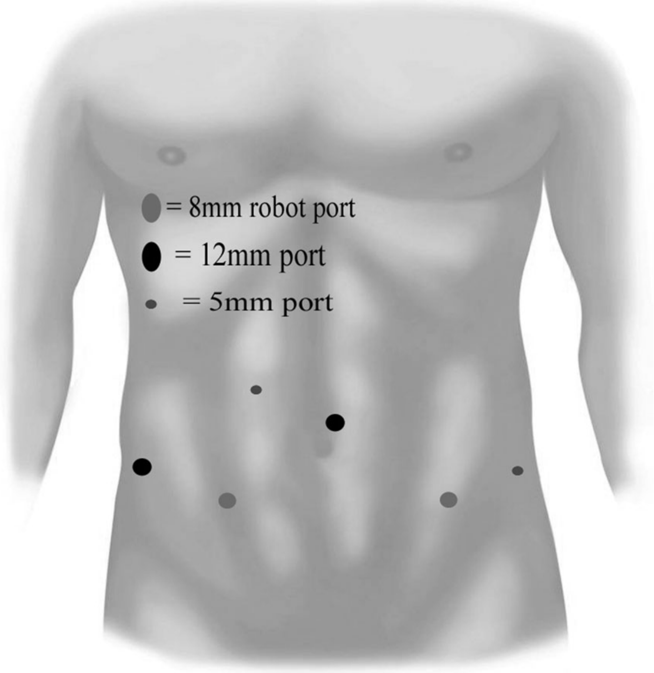

Fig. 4. Size and site of port placements for RARP.

movements of the surgeon's hands. The standard setup of the operation however demands not only the use of three or four laparoscopic ports for the da Vinci robot camera and two or three manipulator arms, but also an additional two to three ports for one or two human assistants or 'patient side surgeons'. The laparoscopic port placement for RARP is detailed in Fig. 4, with the patient positioning shown in Figs. 5 and 6. The robot and its operator require two assistants who are tasked with making 8- to 12-mm incisions and inserting the laparoscopic ports, docking the robot and its instruments with the patient and changing the instruments used by the robot during the procedure. In addition, human control is used for the suction of any blood or urine spilled into the abdominal cavity during the operation which might obscure the operative view, the application of constricting clips (usually hem-o-loc clips by Weck Surgical) onto the vascular pedicle and the passing of the suture and needle into the abdomen by using standard laparoscopic techniques. Thus the procedure is called robot-*assisted* radical prostatectomy, as essential and relatively complex tasks are still accomplished by human 'assistants' as well as by the da Vinci device which is directed by the

Fig. 5. The patient is placed under general anaesthesia with the table sloping head down to allow easier access to the pelvic organs once the ports are placed.

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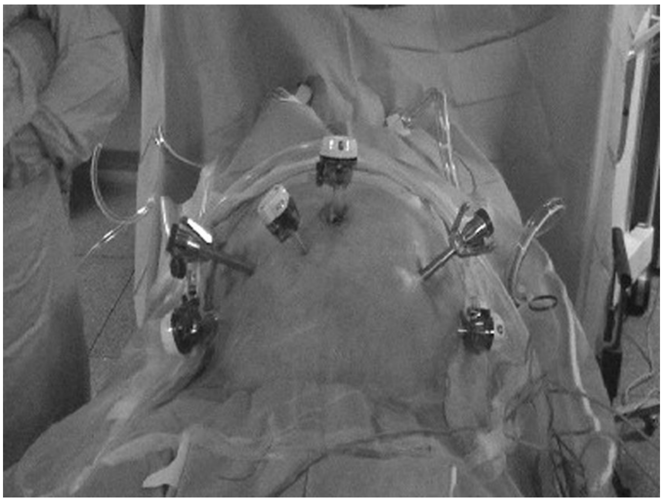

Fig. 6. Abdominal ports placed prior to docking of the da Vinci surgical system.

surgeon. The procedure has developed with the da Vinci machine, as the original three-arm robot has been superseded by a four-arm model which allows the robotic console operator an increased amount of control of retraction, which is used to produce tension in the tissues which are then cut with the various energy sources. Thirty-eight instruments are now available, among which 15 have been recommended by manufacturers for routine use in urological surgery including monopolar and bipolar diathermy combined with graspers and scissors and an ultrasonic energy source.

Outcome of RARP

The National Institute of Clinical Excellence in the United Kingdom published updated guidance on LRP in 2006 and followed it up by guidelines on prostate cancer in 2008. It seems that margin rates and potency after prostatectomy were better for RARP when compared to LRP and open radical prostatectomy (ORP) in a non-randomised fashion. Menon's et al. have reported on the largest series of RARP over a 6-year period. In Detroit, 2766 men consecutively underwent RARP with up to 5-year follow-up. The first 200 and the most recent 200 patients were compared to determine the impact of experience and quality improvement for patients. The mean surgical and robotic console time was 154 min and 116 min, respectively. Estimated blood loss was 100 mL; 96.7% of patients were discharged within 24 h of surgery. At a median follow-up of 22 months, 7.3% of men had a PSA (prostate-specific antigen) recurrence. The 5-year actuarial biochemical recurrence free survival was 84%.[6] Open and laparoscopic surgeons are making the transition to RARP effectively, thus giving their patients the best chance of cure from cancer while maintaining continence and recovery of potency.[7]

Most intra-institutional studies demonstrate better postoperative continence and potency with RARP; however, this needs to be viewed in the context of a paucity of randomised data available in the literature. Experienced open surgeons have been concerned about the apparent reduction in early continence after RARP compared to ORP. Similar concern has been expressed over LRP and is perhaps related to excessive traction on the urethra and surrounding pelvic floor tissues. Tewari and colleagues have described the technique of hitching the bladder up to the arcus tendinus (puboperineoplasty) and reported early continence of 30%, 60%, 88% and 95% at 1, 6, 12 and 18 weeks respectively.[8] Likewise, Patel *et al.* have excellent continence results using a Walsh open surgical 'suspension suture' supporting the urethra to the pubic symphysis[9] and posterior reconstruction of the Denonvillier's fascia. Early potency with or without a PDE5 inhibitor appears to be better with RARP when compared to ORP. With bilateral extended nerve sparing, 80–90% of patients can eventually achieve intercourse.[10] This indicates that perhaps the better vision and more versatile tools of RARP may yield better functional results when surgeons translate this technique, but longer follow-up with validated questionnaires is essential to substantiate these results. In patients with palpable disease on digital rectal examination, needing wide local excision of the neurovascular bundle, the technique of nerve advancement and end-to-end anastomosis has recently been described. A small group of patients appeared to achieve earlier erectile potency after this surgical modification to RARP.[11]

Robot-assisted Radical Cystectomy

While RARP is well established, robot-assisted radical cystectomy (RARC) is evolving. There are very few academic centres performing this challenging procedure. An international robotic cystectomy consortium (IRCC) was established in 2008 to collate data on over 350 patients. RARC takes about 5 h but the operative time is longer if a neo-bladder is created rather than an ileal conduit diversion. The blood loss is typically 150–200 mL, with rapid return of bowel function and hospital stay of around 5–7 days. It has been compared to open and laparoscopic radical cystectomy in a non-randomised manner. The complication rates appear to be lower for RARC with quicker return to full recovery. At a maximum follow-up of 3.5 years, the actuarial overall and recurrence-free survivals after RARC were 95% and 90% respectively.[12]

The technical approach and setup for RARC is similar to RALP (robot-assisted laparoscopic pyleoplasty) for the cystectomy phase. Murphy *et al.* published a recent 'Surgery in Motion' DVD to aid urologists trying to learn this procedure.[13] They described their technique in 23 patients, 19 of whom had ileal loop urinary diversion while 4 had Studer pouch reconstruction. Mean total operative time was 397 (295–600) min. Mean blood loss was 278 (100–1150 mL), with 1 patient requiring a blood transfusion. Surgical margins were clear in all patients, with a median of 16 lymph nodes retrieved. The complication rate was 23%. At a mean follow-up of 17 (4–40) months, 1 patient had died of metastatic disease and 1 with metastasis was alive.

Robot-assisted Laparoscopic Pyleoplasty

Both open and laparoscopic pyeloplasty yield success rates of 90% at relieving pelviureteric junction obstruction (PUJO), although technically the latter demands advanced suturing skills, which may be challenging for the laparoscopist

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to master. This can be simplified by the use of the da Vinci system, which makes suturing easier and quicker because of endowrist technology. Murphy *et al*. reported their technique of RALP in a *Surgery Illustrated* article to simplify learning.[14]

They described a four-port transperitoneal approach. The PUJ is fully mobilised and any crossing vessels noted. The ureter is divided below the PUJ and the renal pelvis transected and reduced. Spatulation of the ureter on its posterior-lateral aspect is accomplished without much difficulty using the angulation on the EndoWrist(tm) scissors.

The technique differs from that described by most authors in that they complete the anterior wall of the anastomosis first rather than the posterior wall. This small technical detail is useful because it simplifies the reconstruction. Traditionally, the posterior wall has been sutured first as it was deemed difficult to access later in the procedure. However, the anterior wall is easier to suture, thereby allowing a technically satisfactory and watertight anterior anastomosis at the outset. Using this method they achieved success in 95% of their patients, with some being discharged from hospital within 18 h after surgery.

Robot-assisted Laparoscopic Partial Nephrectomy

Open partial nephrectomy (OPN) is the standard of care for managing small renal lesions, but minimally invasive approaches are gaining increasing acceptance. Laparoscopic partial nephrectomy (LPN) is an advanced surgical procedure and remains an evolving standard even in the hands of experts. Robotic assistance has been introduced in an attempt to reduce the complexity of LPN. Gettman *et al.* published the first report of robot-assisted laparoscopic partial nephrectomy (RALPN) in 2004.[15]

The next series was reported by Phillips *et al.* from New York in 2005.[16] This group also published a report comparing their series of 10 cases of RALPN with 10 cases of LPN performed by the same surgeons.[17] In both these papers, standard laparoscopy was used to mobilise the kidney, isolate the hilum and expose the tumour capsule before docking the robot. There were no statistically significant differences in operative time, ischaemic time, blood loss, hospital stay, change in creatinine and change in hematocrit between the two groups. The authors concluded that although RALPN is feasible, they could not find any clinical advantage to its use. A recent series of RALPN, published in 2007,[18] comes from Detroit. In contrast to the other two reports, the camera port was placed laterally, which the authors felt prevented the need for extensive colonic mobilisation in addition to better views of the hilum. Lateral camera placement also prevented collisions of the robotic arms. Of the 10 cases, 8 proved to be renal cell carcinoma, 1 oncocytoma and 1 lipoma. There were no recurrences at a mean follow-up of 15 months.

While LPN can be performed by an experienced surgeon with the help of a junior assistant, RALPN in addition to the console surgeon requires the presence of an experienced laparoscopic surgeon at the patient side for hilar clamping and release. This not only takes a degree of surgical control away from the operating surgeon but can also prove to be cost-ineffective and technically challenging.[19]

The Uptake of Robotic Surgery in Urology

In the United Kingdom the da Vinci system had been most commonly used for RALP with robotic pyeloplasty as the second most common procedure. Though our institution has now performed more than 60 RARC operations, this remains an uncommon procedure in the United Kingdom.

Future Developments

Currently, the use of the da Vinci system has achieved advantages in terms of extirpative and suturing precision and in allowing the manipulation of instruments and magnified optics under the control of a single surgeon in a relatively limited intracorporeal space. The technology is however still dependent on both human control and separate patient side surgeons to perform instrument changes for the robot as well as assist with docking and laparoscopic surgery, though these have been markedly improved over the evolution of the da Vinci machine. In the short term, the major advances may be in defining new ways of using existing devices. The limits of application of the existing technology have probably yet to be reached by the majority of surgeons performing robot-assisted procedures.

Though open surgeons are now able to utilise support from a robotic theatre assistant (Penelope CS, RoboticSysTech), which is able to locate an instrument on a voice command and deliver it to the surgeon as well as store it in an instrument tray, this type of technology has yet to be commercially applied to allow robotic instrument changes. Ultimately it may be possible to design master–slave manipulators that are able to achieve complete independence during a procedure; however, the cost of these technologies is likely to be exhaustive and while human surgeons are necessary to provide the initial laparoscopic access and control of the device, it is likely to remain cheaper for humans to perform these tasks.

Future developments may concentrate both on refinements to the technology to allow procedures to be performed with reduced human assistance and perhaps on greater autonomy using image guidance to partially automate steps or provide targeting for a human surgeon. Current collaborations with colleagues in the departments of mechanical engineering and computer science at Kings College include the investigation and development of image-guided robotic surgery, wheeled and air cushion sensors in robotic minimally invasive surgery, haptic feedback from new sensors to robotic instruments, flexible robotics for single-port surgery and natural orifice transluminal endoscopic surgery (NOTES) and the development of metamorphic hands.

Conclusions

Urologists have led the way in clinical robotic surgery in collaboration with colleagues from mechanical and electrical engineering and computer science disciplines. The role of robotics in the management of localised prostate cancer appears to be well established. Robotic renal surgery and cystectomy continue to evolve rapidly. Device design is still in a state of relatively rapid development.

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