Robotic urological surgery: a perspective

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INTRODUCTION

We appear to be heading towards a digital surgical future; high-tech minimally invasive surgery and more recently robotics are examples. Despite these surgical advances it is important to keep things in context. The robotics technology branch at the NASA Johnson Space Center has developed a humanoid robot called Robonaut, with dexterity approaching that of a suited astronaut. This robot can serve with human astronauts in a rapid-response capacity [1]. Compared to such technological advances, robotic urological surgery is still in the early phases of development.

The concept of automation is credited to Aristotle, from the 4th century BC [2]. The word *robot* is derived from the Czechoslovakian *robota,* which means *worker*. It first appeared in Karel Capek's play, *Rossum's Universal Robots*, in Prague in 1921. A surgical robot is regarded as a computer-controlled manipulator with artificial sensing that can be reprogrammed to move and position tools to carry out a range of surgical tasks. The most advanced surgical robots currently are 'master-slave systems' where the surgeon controls robotic arms remotely from a console. Some have argued that these are therefore not true robots, as they lack automation, and have preferred the term 'computer-assisted surgery' for operations with these machines [3]. This debate will continue for some time, as we are many years away from having a true robot such as the Robonaut in surgical practice.

THE MACHINES

Several robotic systems have been described, either in prototype form or clinical practice. At the time of writing there are three main robotic systems in urological practice: the da Vinci^{TM} (Intuitive Surgical Corp., Sunnyvale, CA), the AESOP (Computer Motion, CA, now Intuitive Surgical Corp) and the PAKY-RCM (URobotics, Baltimore, MD).

The da Vinci is the state-of-the-art robotic surgical system, and until recently its competitor was the Zeus robot, but a corporate merger in 2003 resulted in Intuitive Surgical acquiring the rights to both machines. The Zeus is being phased out, making the da Vinci, with its superior performance, the unchallenged master-slave system. The basic principle involves control of three robotic arms (two for instruments, one for a three-dimensional, 3D, camera) by a surgeon seated at a console. A fourth arm for instruments has now been added. The surgeon's finger motions are intuitively translated into movements of the robotic arms, which incorporate 'endowrist' technology, with six degrees of freedom (DOF). Surgical motions are enhanced by filtering of tremors and motion scaling. The 3D camera provides ×6–10 magnification [4]. The main competition to the da Vinci system can be expected from 'mechanical manipulators', which can be used as traditional laparoscopic instruments, and are cheaper. Most of these are in the developmental stages [5].

The AESOP, which allows automated six DOF control of the laparoscope, was introduced in the mid-1990s. Many laparoscopists now regard it as part of the standard operating set-up for laparoscopic radical prostatectomy (RP). Laparoscopic images with the AESOP are steadier, with fewer camera changes and inadvertent instrument collisions than an inexperienced human assistant [6].

Wickham (cited in [2]), in association with Imperial College London, initially developed a five DOF robot for percutaneous nephrolithotomy (PCNL) that could target a calyx to within <1.5 mm. The PCNL robot currently in clinical use is the percutaneous access robot (PAKY-RCM) developed in 1996, and superseded by the Tracker in 2002 (URobotics). The PAKY-RCM has six DOF and can be used with fluoroscopy or CT guidance to improve the accuracy of needle placement. It can be combined with a Smart needle (modified from a percutaneous access needle) to measure bio-impedance and confirm percutaneous access [7].

ROBOTIC UROLOGY

ANIMAL EXPERIMENTS

In a landmark study, the prototype Green Telepresence Surgery System (SRI, International, Menlo Park, CA) was used to perform nephrectomies, cystotomy closures and ureteric anastomoses [8]. Robot-assisted laparoscopic pyeloplasty in swine, using the Zeus system, achieved a watertight anastomosis in five of six animals [9]. Robotic laparoscopic nephrectomy required significantly longer than conventional laparoscopic nephrectomy (85 vs 39 min), as did robotic adrenalectomy vs pure laparoscopic adrenalectomy (51 vs 32 min). The same group went on to compare the da Vinci and the Zeus systems on 14 pigs, reporting that the learning and operating times during nephrectomy, adrenalectomy and pyeloplasty were shorter with the da Vinci system. In that study the technical movements appeared more intuitive with the da Vinci system [10].

CLINICAL APPLICATIONS

TURP: We owe the introduction of robotics in clinical urology to Wickham and his colleagues; in the late 1980s a collaborative venture between the Mechanical Engineering department at Imperial College and Guy's Hospital, London, saw the development of a TURP robotic frame. The resection was based on a potato model of the prostate and developed into the Probot [11], a robot with automated prostate recognition using ultrasonography, and capable of performing TURP or prostatic vaporisation. Preliminary results showed a significant improvement in symptoms and peak flow rates [11].

PCNL, nephrectomy and adrenalectomy: After initial reports regarding its efficacy in pigs and humans, regular clinical use of the PAKY-RCM arm is underway, with the Johns Hopkins series of 23 patients undergoing robotic PCNL being compared to patients undergoing conventional manual PCNL. Robotic insertions compared favourably for time to access, number of attempts and estimated blood loss [12].

The first clinical robot-assisted nephrectomy used the Zeus system; the operative time was 200 min and the estimated blood loss <100 mL. The da Vinci robot was used for transperitoneal adrenalectomy in two patients with adrenal tumours (one right, one left; tumours 4.5 and 3 cm). The operative time was 110 and 165 min, the blood loss 50 and 100 mL, and the hospital stay 2 and 3 days [13].

A combination of the da Vinci robot and hand-assisted laparoscopy was used for live-donor nephrectomy in 12 patients. The median operative time was 166 min, blood loss 68 mL, warm ischaemia time 79 s and hospital stay 1.9 days. None of the recipients had delayed graft function [14]. An interesting case of open kidney transplantation with da Vinci robotic assistance has been reported. Vascular and ureteric anastomoses were made robotically, with a total operative time of 178 min, and excellent allograft perfusion and function [15].

Robot-assisted pyeloplasty has been reported in adults and children, using 5-mm instruments in the latter. In nine patients undergoing Anderson-Hynes pyeloplasty with the da Vinci robot the mean operative time was 139 min, suturing time 62 min, and all were successful at a short mean follow-up of 4.1 months [4]. This group compared robotic Anderson-Hynes and Fengerplasty to conventional laparoscopic pyeloplasty in 12 patients, and found robotic procedures to be quicker, as was suturing [16].

RP

In no other procedure has the clinical expansion of urological robotics been more profound than RP, largely through the contributions of Menon's team from Detroit. Initial pioneering reports from European centres showed prolonged operative times of 315–450 min in groups of 10 patients or fewer. The Detroit experience clearly indicates that once learned, the outcomes of robotic surgery improve. It has been suggested that for established open surgeons the training for robotic RP may be somewhat shorter than for pure laparoscopy. In >300 robotic RPs the operating time was 120–160 min, with a mean blood loss of 150 mL. None of the patients needed a blood transfusion [17]. This compares favourably with an operating time of 232 min, blood loss of 370 mL and a transfusion rate of 5% after laparoscopic RP [18]. Over 95% of RP patients were discharged within 24 h. The median specimen Gleason score was 7 and tumour volume 7 mL. At 6 months, 96% of patients after robotic RP were continent and 60% of initially potent men had unassisted intercourse. In comparison, 93% continence and 86% potency rates after open RP using patient-reported quality-of-life surveys were achieved in the best hands [19]. Robotic RP costs ≈$150 more than open RP, but in recent months, costs have favoured robotic surgery, as the operating times decreased [17].

In their unrandomized comparison of 200 robotic with 100 open RPs, the Detroit team reported similar operative times and none of the patients needed a blood transfusion after robotic RP, compared with 67% after open RP. There were four times as many complications after open RP [20]. In their single-centre experience, the hospital stay was 1.2 days for robotic, 1.3 days for laparoscopic and 3.5 days for open RP; the respective catheter duration was 7, 8 and 15 days [17], although with a continuous suturing technique for the urethrovesical anastomosis, the catheter duration after robotic RP has reduced to 4 days [21], similar to laparoscopic RP in other centres [18]. Experienced open surgeons have also tried to reduce the catheter duration to 7 days in ≈75% of their patients [22], although this is still longer than that reported after laparoscopic and robotic RP. In Detroit, positive margins were reportedly more frequent after open surgery, at 23% for open and 9% for robotic surgery [20]. Notably, the technique of evaluating pathological margins appeared to be different in the two groups. While the open cases had step-section microscopic examination of the prostate specimen, as is routine at most institutions, in the robotic group periurethral soft-tissue biopsies were evaluated on frozen sections, which may have served to 'reduce' the apical positive margin rate. In comparison, expert open [23] and laparoscopic [18] surgeons have reported positive surgical margins of 12.8% and 13.7%, respectively.

CYSTECTOMY

The initial robot-assisted laparoscopic radical cystectomy and Hautmann neobladder was performed in a 58-year-old man, with an operative time of 8.5 h and blood loss of 200 mL [24]. The Detroit group reported robot-assisted nerve-sparing radical cystoprostatectomy and urinary diversion. The specimen was retrieved through a 5–6 cm incision which was then used to create either an ileal conduit or neobladder by open surgery. The neobladder was sutured to the urethra robotically. The mean blood loss was <150 mL and the margins were negative in all 17 patients [25].

Sural nerve grafting: With the da Vinci system sural nerves were grafted after RP in three potent men, aged 48, 49 and 59 years. The harvested nerve was grafted robotically using 4–6 interrupted perineural 6/0 or 7/0 polypropylene sutures. The mean operative time was 6.5 h, of which 1.5 h were for nerve grafting [26]. The current follow-up showed a return of potency in two men, one with bilateral grafts.

Other procedures: Augmentation cystoplasty has been performed with the da Vinci system but no data are currently available [4].

TRANS-OCEANIC TELEROBOTICS

Telementoring in urology has been pioneered by the Baltimore group, who have telementored several procedures in Austria, Singapore, Italy and Germany, including laparoscopic adrenalectomy, radical nephrectomy, varicocelectomy, renal cyst ablation and PCNL [27]. Telerobotic control is conducted using ISDN lines; Internet connections can also be used and are cheaper. The concept of having a surgeon in one country performing an operation in another via a computer-assisted link became reality in 2001, when a laparoscopic cholecystectomy was performed on a patient in Strasbourg by a surgeon in New York (Lindbergh operation) [28]. The time delay can significantly affect surgical performance, but if the lag time is

<700 ms the surgeon can learn to compensate.

RANDOMIZED CONTROLLED TRIAL OF TELEROBOTICS

To our knowledge the only randomized controlled trial of telerobotics in urology was the recent transatlantic study between Guys Hospital and Johns Hopkins. Statistical analysis with adequate power required a total of 304 telerobotic PCNLs, which could not be ethically supported in humans and was legally unacceptable in animals in the UK. A specially designed and validated kidney model was used (Limbs and Things, Bristol, UK) and either a robotic arm or a urologist (152 procedures each) inserted a percutaneous needle. Thirty remote procedures were performed from Baltimore via four ISDN lines. The trial showed the robot to be slower but more accurate than humans. All urologists made fewer needle passes while using the robotic arm. A cross-over trial subsequently showed that the robot can be controlled equally well from the UK to USA as it is in the opposite direction [29].

ADVANTAGES: PERCEIVED AND REAL

The perceived advantages of robot-assisted surgery include precise movement of the robotic arms, endowrist technology and 3D stereoscopic vision. For the novice, robotics seems to make intracorporeal suturing easier than in pure laparoscopic surgery. The 'fulcrum effect' in conventional laparoscopic surgery, whereby the instrument tips move in the opposite direction to the surgeon's hand around the port site (fulcrum) is counter-intuitive. Conversely robotic movements are intuitive, where the instrument tips move in the same direction as the surgeon's hands. However, experienced laparoscopic urologists feel that these are not true advantages of robotic surgery and can easily be overcome by the rigorous practice of conventional laparoscopy. Most laparoscopic surgeons, although seeing objects in 2D on a flat screen, think in 3D. They are also able to suture effectively and precisely intracorporeally with no need for a robot [3]. To be good at laparoscopic surgery requires hard work and application, but that is true for anything in life. Even robotics! To justify its expense and establish its position firmly in urology, robotics must be better than open surgery and conventional laparoscopy, not just equal. Evidence as to whether an experienced laparoscopic urologist can improve the operative skills and outcomes using robotics is not available. However, robotics provides some real advantages; the surgeon's seated position at the console is more ergonomic; motion scaling can be a helpful computational adjunct. These machines make remote surgery possible, in principle allowing a patient at a remote location to receive care from an experienced surgeon [29]. Finally, robotic technology is sure to improve even further in future.

DISADVANTAGES

The costs of installing a robotic system, its subsequent maintenance and the price of disposable instruments currently border on the prohibitive. Pressures on healthcare funding differ greatly among countries and this is reflected in the distribution of surgical robots. It is anticipated that the price of these robots will decrease, and savings for patients and hospitals because of the advantages offered by robotics will ultimately balance the initial expenditure. Current robotic systems lack tangible force-feedback. The da Vinci is a large machine that may possibly become smaller in the future. Any improvements must be introduced as upgrades, as buying a complete new system may be financially unacceptable for many. The instrument size and design needs to be improved and the tools themselves need to last longer. Finally, although some robots such as the AESOP can facilitate solo surgery, this has negative implications for the training of juniors, who need to learn camera and instrument manipulation as part of their laparoscopic skills.

KEEPING UP WITH THE JONES'S

Owning a robot because your neighbour has one is almost fashionable, but a rather expensive prospect. Marketing expertise should not be the driving force for this technology. Instead, the drive to acquire these machines should stem from a true desire for robust scientific evaluation. This should involve not just urologists but health economists and social scientists. The Jet Propulsion Laboratory at the California Institute of Technology has formulated a new technique for evaluating human-robot system performance, which involves complex mathematical methods [30]; a similar method could be used to evaluate the true performance and safety of surgical robots.

OUR VIEW OF THE FUTURE

Surgical robotics has a bright future, but rigorous scientific evaluation is necessary. Biomedical, ethical and moral issues need to be addressed now to avoid an uncontrolled and unprepared future [31]. Legal and licensing barriers will need to be overcome before telesurgery becomes clinically viable. Shared responsibility for robotic failures needs to be in place for telerobotic procedures. As surgeons we may become too engrossed with new technology and forget our patient's desires and satisfaction, which need assessing by validated patient-satisfaction surveys.

We have come a long way since the initial enthusiasm for urological robotics [32]; good quality evidence is at present lacking. In addition to expert opinion, prospective data comparing robotic to conventional open and laparoscopic surgery is mandatory. Randomized trials may not be possible because of patient demand, but should at least be attempted. It is anticipated that nanotechnology will enter the field of surgical robotics, but the basic principles of flexibility and adaptability of instruments and their design to suit a variety of procedures need to be maintained. Robotics is rapidly becoming a part of the operating room of the future and should be seen not as a revolution, but a well-grounded evolution [33].

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CONFLICT OF INTEREST

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Abbreviations: **RP**, radical prostatectomy; **3D**, three-dimensional; **DOF**, degrees of freedom; **PCNL**, percutaneous nephrolithotomy.