Robotics in urology

Twenty years after it was introduced, robotic surgery has become more commonplace in urology – we examine its current uses and controversies

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There has been a significant interest in minimally invasive surgery (MIS) in the past two decades in an attempt to reduce morbidity, expedite recovery and decrease hospital stay.[1] MIS approaches – both conventional laparoscopy and robot-assisted approaches – have replaced a significant number of open surgical techniques. Despite its obvious benefits, conventional laparoscopy has its challenges with inferior quality 2D vision and limited wrist manoeuvrability. Robotic-assisted laparoscopic surgery (RALS), with its 3D high-definition images, enhanced endo-wrist dexterity, precise hand–eye coordination, physiological tremor filtering, and motion-scaling has emerged as a viable alternative option, with a potential to mitigate the limitations of conventional laparoscopic surgery.

The term 'robot' was coined by the Czech playwright Karel Capek in his 1921 work *Rossum's Universal Robots*.[2] It comes from the Czech word 'robota', which translates as 'forced work'. In Capek's play the robots helped their human masters with various tasks before revolting to seek world domination. How prophetic it proved when almost a century later robotic systems have begun to dominate the surgical landscape in urology.

The robotic surgical systems currently used are almost solely those derived from the original da Vinci® system developed by Intuitive Surgical (Sunnyvale, US). Although other systems had been used, it was the da Vinci® system that has provided the revolution in the field. It is described as a 'master–slave' system, which comprises of a surgeon's console (master), a patient-side robotic cart (slave) and an image processing stack (Fig 1). The console is designed as a closed system comprising a 3D video system and an in-line view. Newer models offer high-definition vision. The robotic cart consists of four robotic arms manipulated by the console; one arm controls the camera and three are used for surgical instruments. The arms use Endowrist© technology (Fig 2), which provides 7 degrees of freedom and 90-degree articulation upon which instruments are loaded and introduced to the body via cannulas. As of 2016, some 2,500 da Vinci® systems have been installed and have performed almost half a million procedures.[3]

The da Vinci® robot was initially developed for cardiac surgery in 1999. Modern-day RALS is, however, predominantly dominated by urological, gynaecological and visceral surgery. In the UK the robotic systems have increasingly become the workhorse in a number of urological units. This article aims to discuss the current status of robotic surgery in contemporary urological practice.

Radical prostatectomy

Historically, open retropubic radical prostatectomy was considered the gold standard for treatment of localised prostate cancer since Terrence Millin's first description in 1947.[4] The technique can be associated with a degree of morbidity and potentially longer convalescence. As the field of laparoscopic surgery grew in the 1980s, it wasn't long before the first laparoscopic radical prostatectomy (LRP) was undertaken in 1992. The primary limitation of LRP was the challenge of performing the vesico-urethral anastomosis in the pelvis with limited manoeuvrability.

The development and introduction of the da Vinci® surgical system in the late 1990s proved to be a watershed moment in both urology and robotic surgery. With 3D visualisation and jointed laparoscopic instruments providing 7 degrees of freedom, the da Vinci® system provided the perfect marriage of the minimally invasive and magnified advantages of LRP with the dexterity of an open procedure. More than a decade since the first reported robot-assisted laparoscopic radical prostatectomy (RALP), it is widely accepted as the surgical modality of choice for radical prostatectomy in well-resourced countries.[5,6]

Figure 1 The da Vinci® Si robot system comprising surgeon console, robotic cart and image-processing stack. *Image reproduced with permission from Intuitive Surgical Inc, Sunnyvale, California, US.*

It is estimated that by 2020 in the US 80% of radical prostatectomies will be performed robotically.[15] Undoubtedly, the main benefit in its uptake has been a shorter learning curve compared with LRP. The number of reported cases to achieve 4-hour proficiency for RALP is 20 cases compared with 80 cases for LRP.[7,8]

With the robotic platform, prostatectomists worldwide discovered the potential for more intricate operating. Consequently the technique of RALP continues to evolve in a quest to achieve superior oncological and functional outcomes. Furthermore, contemporary understanding of surgical anatomy of the prostate – particularly the neurovascular anatomy – has improved with superior vision of the robotic technology. Since the first description of the prostate neurovascular anatomy in 1982 by Walsh *et al*, a number of modern-day robotic prostatectomists have added to the understanding of neurovascular anatomy.[9] This has enabled surgeons to develop improved techniques for

Figure 2 Endowrist© instrument with seven degrees of freedom. *Image reproduced with permission from Intuitive Surgical Inc, Sunnyvale, California, US.*

the preservation of neurovascular anatomy. Menon *et al* hypothesised that the anterolateral aspect of the periprostatic fascial layer contained neural tissue that could be preserved and coined the term 'Veil of Aphrodite' to describe it. Preservation of this veil improved potency postoperatively compared with standard nerve-sparing techniques.[10] Tewari *et al* described the risk-stratified incremental nerve-sparing approach based on the understanding of layers of periprostatic fascial dissection.[11] Bocciardi's

Figure 3 Radical prostatectomy

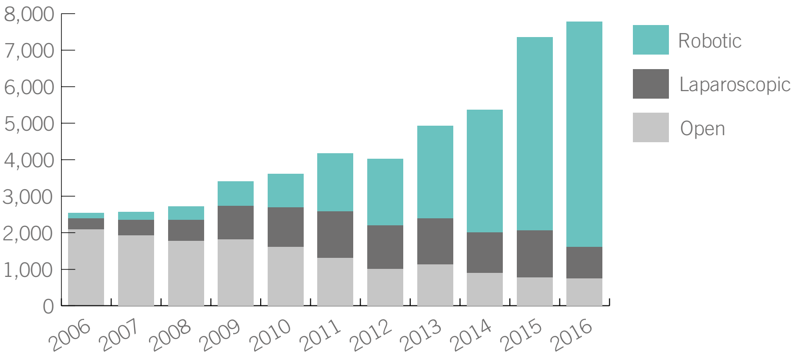


Figure 4 Partial nephrectomy

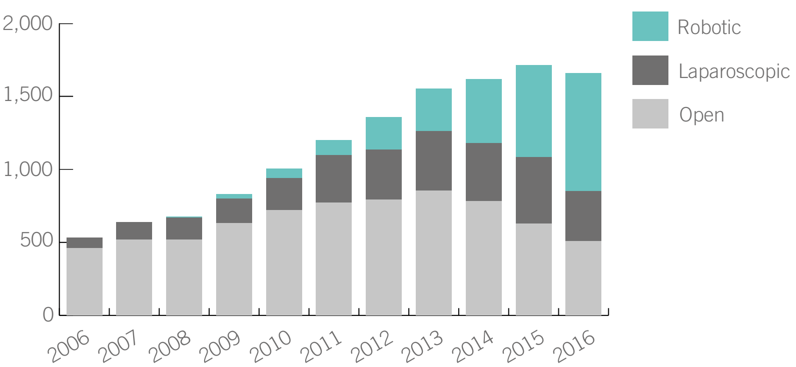
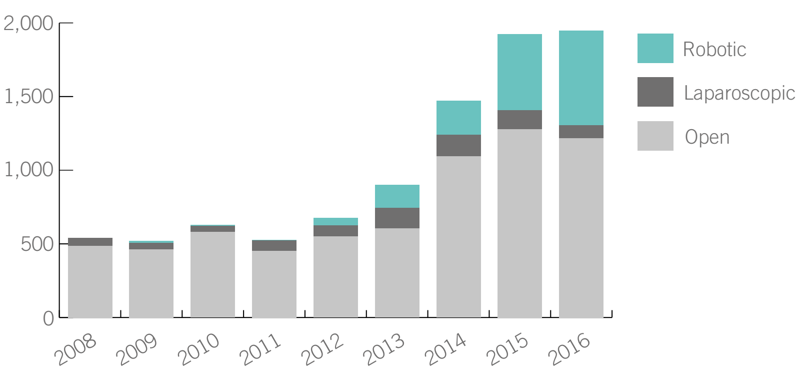


Figure 5 Radical cystectomy



Retzius-sparing RALP has recently gained popularity.[12] In this approach, the surgeon passes through the Douglas space, avoiding the anterior compartment with potentially immediate return of erectile function and continence. This approach marks another landmark in the evolution of the RALP technique. Other technical adjustments have included bladder neck preservation, periurethral suspension and reconstruction, preservation of urethral length, puboprostatic ligaments and endopelvic fasica – all of which have been greatly facilitated by the robotic system.[13]

Despite probably the fastest-growing and evolving robotic procedure, level 1 evidence comparing RALP with its counterparts has been limited. Asimakopoulos *et al* reported the first randomised control trial (RCT) comparing LRP and RALP.[14] The study reported significantly better erectile function recovery in the RALP cohort. However, perioperative and continence outcomes were similar for the two groups. Porpiglia *et al* reported an RCT of 120 patients comparing RALP and LARP.[15] The trials also reported similar perioperative, pathologic outcomes and complication rates between the two cohorts. Short- and long-term continence and erectile function rates were, however, significantly better in the RALP cohort. Yaxley *et al* recently reported an RCT of 326 patients comparing RALP and open radical retropubic prostatectomy, concluding similar functional outcomes between the two cohorts.[16] However, operating time, intraoperative adverse events, estimated blood loss and hospital stay were significantly lower in the RALP cohort. Interestingly, in this trial there was a significant disparity in the surgical experience of the robotic and open surgeons. The RALP and open surgeon had performed 200 and 1,500 prostatectomies respectively before the start of the trial, which emphasised the significantly lower learning curve for the robotic approach.

Systematic reviews, which included cohort studies, have found significant improvement in 12-month incontinence rates (7.6% *vs* 12%) and potency rates (60% *vs* 48%) of RALP compared with open prostatectomy – with no difference in positive margin or biochemical recurrence rates.[17,18] A nationwide series of almost 20,000 radical prostatectomies showed that RALP had significantly lower blood transfusion and overall complications rates and shorter length of stay but no difference in mortality.[19] Currently follow-up in existing studies is relatively short, which precludes firm conclusions regarding oncological outcomes.

The cost of the robotic system is undoubtedly the biggest disadvantage. Even allowing for the shorter hospitalisation, RALP still incurs an additional £1,200 per case compared with open prostatectomy; although it is possible to achieve cost-equivalence in high-volume centres (>10 cases/week).[8,20]

Radical cystectomy

The gold standard treatment for muscle-invasive and high-risk superficial bladder cancer involves a radical cystectomy, extended pelvic lymph node dissection and urinary diversion. Despite improvements in surgical techniques and hospital care, the open radical cystectomy (ORC) remains a highly morbid procedure – with a reported morbidity and mortality of 50% and 5% respectively.[21,22] The urinary diversion, with its reconstructive aspects, significantly contributes to the morbidity and prolonged recovery from the procedure. This step is particularly challenging with the conventional laparoscopic approach. Menon *et al* reported the initial series of robotic-assisted radical cystectomy (RARC) series in 2003.[23] There has been reasonable uptake of the technique since this initial reported series, with more than a quarter of cystectomies in the UK performed robotically in 2016.[24]

The International Robotic Cystectomy Consortium (IRCC), a retrospective multi-institutional database of robotic cystectomies since 2003, is possibly the world's largest database on robotic cystectomies and reports on complications and oncological outcomes. The consortium report a Clavien Grade 3 or higher complication rate of 19% associated with RARC. The 30- and 90-day mortality for RARC was reported at 1.3% and 4.2% respectively.[25] At a median follow-up of 67 months, the IRCC reported 5-year recurrence-free survival and cancer-specific survival of 67% and 75% respectively.[26] A concern with the robotic approach was the ability to perform a good-quality extended pelvic lymph node dissection. The analysis from the IRCC reported that more than 80% and 40% of the patients from the consortium had ≥10 and ≥20 lymph nodes sampled respectively; it concluded that the rate of lymphadenectomy during RARC was comparable with ORC.[27] In the initial series of RARC, the urinary diversion was performed with an extracorporeal approach.[23] Modern-day surgeons perform the urinary diversion with an intracorporeal approach. In the IRCC the proportion of patients receiving intracorporeal urinary diversion has increased from 9% in 2005 to 97% in 2016.[28] The IRCC reported shorter operating time, lower estimated blood loss, transfusion and gastrointestinal complication rates with intracorporeal urinary diversion when compared with extracorporeal urinary diversion.[29] Despite the purported benefits of RARC, RCTs haven't conclusively conferred its superiority over ORC. Bochner *et al* have published the largest complete RCT comparing ORC and RARC. The trial randomised 118 patient and reported similar 90-day Clavien Grade 2–5 complications of 62% and 66% for RARC and ORC respectively.[30] Furthermore, the trial failed to demonstrate superiority of RARC over ORC for hospital stay, pathologic outcomes and quality-of-life (QoL) outcomes.

The RAZOR trial – the first phase 3, multicentre, prospective randomised trial comparing ORC and RARC – is currently underway.[31] The trial has recruited 350 patients and will be the largest trial comparing the 2 techniques once it is completed. The preliminary results from the trial suggest that the estimated blood loss and blood transfusion rates were significantly lower in RARC cohort. They also report a trend toward lesser hospital stay with RARC. However, major complications (Grade III and above), number of lymph nodes sampled, overall positive margin status, positive bladder soft-tissue margin rates were similar between the two techniques.[32] The two-year recurrence-free survival rates are yet to mature and are currently awaited.

As with RALP, cost is an issue with performing RARC. An RARC with an ileal conduit adds an additional £1,200 per case whereas an orthotopic neobladder adds £2,800 compared with an equivalent ORC.[30,33] Undoubtedly, it is an expanding procedure and as surgeon experience improves outcomes may follow; the question of whether totally intracorporeal cystectomy is superior to ORC remains unanswered.

Partial nephrectomy

Partial nephrectomy is the surgical intervention of choice for small renal masses.[34,35] The procedure involves excision of the renal mass and subsequent renorrhaphy of the renal defect while the renal artery is clamped. This step, therefore, needs to be performed within a certain time limit, depending on ischemia techniques, in order to avoid permanent renal injury. Traditional open partial nephrectomy (OPN) involves large muscle-cutting abdominal or flank incisions that may involve rib removal and, as such, can have long hospital stays and recovery periods.[36] Laparoscopic partial nephrectomy (LPN) was first performed in 1993, with the goal of avoiding morbidity of such large incisions.[37] The main challenge with conventional LPN is the ability to perform an effective renorrhaphy within quarter of an hour while the renal artery is clamped. Gill *et al* reported outcomes of a single surgeon performing more than 800 cases. The authors reported mean ischaemic time of 32 minutes for the first 500 cases. An ischaemia time of less than 20 minutes was achieved in only 15% of cases, emphasising that LPN is a technically challenging procedure – even in the hands of high-volume experts.[38] The reconstructive challenges of LPN have been significantly mitigated, with the robotic platform with the first robot-assisted partial nephrectomy (RAPN) performed in 2004.[39] The reported learning curve for a RAPN is significantly lower than LPN (15–25 cases compared with 100–150 for LAPN).[40] In the UK, 47% of partial nephrectomies in 2016 were performed robotically.[41] In a recent systematic review of 25 non-randomised comparative studies that included nearly 5,000 patients, RAPN was being performed in larger and more complex renal masses when compared with LPN.[42] Despite the complexity and larger size of the renal masses, RAPN had lower conversion rates, warm ischaemia time and overall and major complication rates.

Whereas other robotic procedures are more costly than their open counterparts, the median cost of partial nephrectomy does not significantly differ by modality.[43] The increased cost of the robotic system and maintenance is offset by the reduced hospitalisation and complication rates.[44]

Robot-assisted pyeloplasty

Pelvicoureteric junction obstruction (PUJO) is a congenital ureteric abnormality affecting 1 in 20,000 live births.[45] The open dismembered pyeloplasty has been the standard of care, with reported success rates of more than 90%.[46] As with other open renal surgery, it was associated with long recovery times and hospital stay and so minimally invasive alternatives have been explored. Balloon dilatation and endopyelotomy achieved reduced morbidity but success rates of only 60%.[47] The first laparoscopic pyeloplasty was performed in 1993 and early series reported similar success rates to the open approach but with lower morbidity.[48,49] As with other laparoscopic procedures, pyeloplasty is technically challenging with a steep learning curve. However, laparoscopic pyeloplasty became more widely accepted, although limited to large-volume centres.[36] The considerable amount of intracorporeal suturing required for the procedure made it a prime candidate for the robotic approach; the first robot-assisted pyeloplasty was performed in 2002.[50] The advantages over the laparoscopic approach include shorter learning curve, enhanced tissue manipulation and improved visualisation.[51] No RCTs comparing robotic pyeloplasty with other approaches exist; however, laparoscopic pyeloplasty has shown superiority in analgesic requirements and length of stay, with similar success rates – although with longer operating time than open pyeloplasty – in RCTs.[52,53] Meta-analyses have shown that robot-assisted pyeloplasty has similar success rates but lower analgesic requirements and length of stay compared with both laparoscopic and open approaches in adult and paediatric populations.[51,54,55,56] Furthermore, it has a shorter operating time than laparoscopic – but longer than open approaches. As experience has improved, urologists have used the robotic approach in the technically challenging scenario of redo pyeloplasty, with small case series exhibiting its feasibility.[57]

> *The increased cost of the robotic system and maintenance is offset by the reduced hospitalisation and complication rates*

Cost-effective analysis has shown that compared with open pyeloplasty the robotic approach is significantly more expensive (£2,500/case) but no different to the laparoscopic approach.[33]

Robot-assisted radical nephrectomy and nephroureterectomy (RARN/RARNU)

Laparoscopic radical nephrectomy (LRN) has largely supplanted the traditional open nephrectomy in the past 20 years owing to shorter hospital stay, less blood loss and quicker recovery, with no difference in oncological outcomes.[58] As an extirpative procedure, it is less technically challenging to perform laparoscopically than those outlined above, which somewhat negates the advantages that the robotic system offers.[44] Although it has been used, RARN has an increased operative time (associated with docking the system), higher cost (£8,000/case) and no improvement in clinical outcomes over laparoscopic nephrectomy.[59]

There may, however, be a role for RARN in renal tumours where standard laparoscopy is contraindicated, such as large tumours with vena caval thrombus. Small series have reported promising results for RARN, with vena cava thrombectomy and complex nephrectomies may become an indication for RARN.[60]

For the same reasons that RARN hasn't dislodged LRN, RARNU hasn't proliferated clinical practice, given the good results achievable with laparoscopic radical nephroureterectomy (LRNU). The improved dexterity of RARNU has been purported to improve distal ureteric dissection and bladder closure, as well as providing better vision for potential lymph node dissection.[61] Early reports of RARNU required the system to be repositioned and redocked; however, newer techniques have eliminated this need.[62,63] A systematic review showed equivalent perioperative and oncological outcomes but possibly lower postoperative mortality and complication rates of RANU over LRNU.[64]

Other robotic procedures

Given the success of the robotic system and its proliferation into the urological mainstream, it would seem that no urological procedure is safe from its extending reach. Below we will outline some of the urology procedures that have been reported but yet to become mainstream applications of the robotic system.

Although not commonly performed, ureteral reconstruction, reimplantation and ureterolysis have traditionally involved a laparotomy (with its associated morbidity). The ergonomics, dexterity and minimally invasive nature of the robotic system lend itself well to these delicate procedures. The first robotic ureteral reimplantation was reported in 2004 and the first robotic ureterolysis with omental wrap in 2006.[65,66] Although series are relatively small, they do appear to show lower morbidity – with similar success rates to the open approach.[67]

Bladder reconstruction with cystoplasty is also an infrequent procedure, mainly owing to the rise of botulinum toxin. However, it too involves a lower midline approach and purely laparoscopic techniques are not practical owing to the amount of intracorporeal suturing required. Robotic cystoplasty has been reported, with similar outcomes to open approach; although a significantly longer operating time.[68] Similar findings have been seen with robotic mitrofanoff.[69]

The robotic system has also been applied successfully to renal transplantation. In most reports, the procedure does involve a periumbilical incision for graft introduction whereas others have used a transvaginal incision. Early reports indicate equivalence in functional graft outcomes with an open approach. Minimally invasive approaches did show lower postoperative complications of wound infection and hernia, with shorter recovery times, but did have longer ischaemia and operating times.[70]

The robotic approach has also been used for simple prostatectomy (RASP), with the first report in 2008.[71] It confers similar advantages to RALP in prostate surgery. Traditional open prostatectomy for large glands is inferior to RASP for blood loss, transfusion, length of stay and overall cost.[72] However, with HoLEP now the standard of care for large glands, RASP is associated with longer operating times, higher transfusion rates, longer hospital stay and catheter indwelling time on direct comparison, which is likely to limit RASP's role in BPH treatment.[73]

Not content with its use in oncological and reconstructive urology, the robotic system has also tried its hand at management of stone disease. Case series have described the feasibility of robotic ureterolithotomy for large stones; however, this role is likely to be limited, given the results and durability of traditional endoscopic management.[74]

Others have used the magnified 3D view that the robotic system offers to perform a variety of microsurgical procedures, including varicocelectomy, vasectomy reversal, spermatic cord denervation and testicular sperm extraction.[75] So far these have not exhibited superiority over the use of an operating microscope to justify the high cost.

Training

As robotic surgery expanded within the field of urology, many with established practices in laparoscopic and open urological procedures were faced with the challenge of training to use this technology. Although seen as an evolution of laparoscopy, the novice to the robotic system has to learn to control the console, perform procedures without haptic feedback and use instruments with greater degrees of freedom. It had become apparent that a validated, structured curriculum and accreditation was needed for this new generation of urologists. This would allow acquisition and development of the basic and complex robotic skills required in a gradual manner centred on patient safety, with an appropriately short learning curve.[76] Thus the British Association of Urological Surgeons (BAUS) has produced a curriculum for the UK whereas the European Association of Urology (EAU) created its own subsection, EAU Robotic Urology Section (ERUS), with a robotic curriculum and participating fellowship centres.[77,78] The recommendation for training begins with e-learning modules that are provided by da Vinci®. Simulation-based training includes virtual reality simulators – the da Vinci® Skills Simulator (dVSS), which attaches to the back of the da Vinci® console, is the most commonly used. Dry lab exercises are also used for basic manoeuvres (eg suturing), with models for more advanced techniques (eg anastamosis). Wet lab simulation provides either animal or human cadavers, although these are not widely accessible and often rather costly.

Mentorships or fellowships provide the next part of training and this consists of a modular fashion that is tailored to the procedure. Da Vinci® offers a dual robotic console that is recommended for use in training. Instrument control can be passed between the 2 consoles allowing the mentor or trainer to visualise in 3D, as the trainee operates and intervenes if necessary. Final sign-off occurs when the trainee achieves appropriate quality indicators specified in the curriculum. Such validated structured training programmes ensure effective acquisition of robotic skills.[78]

The future

The da Vinci® robotic system has revolutionised the field of urology in the developed world and has now established robotic surgery in the public consciousness. Intuitive Surgical currently own more than 1,500 patents and remains largely unchallenged in the field. During this proliferation of robotics, other companies have developed various systems in an attempt to gain some the market share. Most have been abandoned whereas some have recently become available (eg Teleap ALF-X). Other systems are ongoing projects that are awaiting clinical trials.[79] It is hoped that should rivals be able to enter the market with alternative systems then competition should drive down the costs, thereby making systems more accessible.

More recent advances include the use of single site surgery, using the degrees of freedom offered by robotic instruments in the da Vinci® Single Site surgical platform. To date, it has been used in selected cases of partial nephrectomy and pyeloplasty.[80,81] However, feasible early drawbacks such as external collisions, limited bedside assistance workspace and inadequate instruments have been noted. Other designs currently in the experimental stage include the Raven project, which is a system designed to allow two surgeons to operate on the same patient simultaneously, as well as looking to expand into the role of battlefield or underwater remote surgery.[82] Autonomous robotic technology has also been developed – eg the Smart Tissue Autonomous Robot (STAR), which has been used in porcine models to perform autonomous intestinal anastomosis.[83] Further technological advances are expected to come into the market in the next decade.

Conclusion

Twenty years after the first urological robotic procedure, it has become an established part of the urologist's armamentarium. For some procedures it has become accepted practice and this has allowed it to be explored in the entire spectrum of complex reconstructive and extirpative urology procedures. Despite its widespread adoption, controversy still surrounds it; the lack of level I evidence, unknown long-term oncological and functional outcomes and the not insignificant expense are still issues. Current evidence will improve and mature and, if new systems emerge, market costs should lower. Whether you love it or loathe it, robotic surgery now has an irreversible role in urology.

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