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Past, present and future of urological robotic surgery

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The first urologic robotic program in the world was built at the Vattikuti Urology Institute, Henry Ford Hospital Detroit, Michigan, in 2000 under the vision of surgical innovator, Dr. Mani Menon for the radical prostatectomy. The robot-assisted radical prostatectomy continues being modified with techniques to improve perioperative and surgical outcomes. The application of robotic surgical technique has since been expanded to the bladder and upper urinary tract surgery. The evolution of surgical technique and its expansion of application will continue to improve quality, outcome parameters and experience for the patients.

Keywords: Cystectomy; Nephrectomy; Prostatectomy; Robotics

A PERFECT STORM

The Vattikuti Urology Institute (VUI) at Henry Ford Hospital in Detroit, Michigan, USA established the first urologic robotic surgery program in the world in 2000. It would not have happened without 3 crucial factors: an innovative idea, an experienced surgeon with tremendous foresight, and considerable philanthropic funding. In keeping with the legacy of Henry Ford and the spirit of innovation, we sought to develop and improve upon techniques of minimally invasive prostate surgery. Initially, Dr. Mani Menon and his colleagues adopted a laparoscopic approach for radical prostatectomy in collaboration with Dr. Guy Vallencien and Dr. Bertrand Guillaneau, skilled surgeons from France. However, it became apparent that due to the different body habitus of American men compared to Europeans, the laparoscopic approach was not as comparable to the retropubic approach as expected. The advent of a robotic surgical system approved for cardiac surgery offered a potential solution. Dr. Menon's experience informed his foresight in seeking to apply the surgical robot to urologic surgery. With the generous support from the Raj and Padma Vattikuti Foundation, a perfect storm gathered to initiate our journey into the robotic era.

RADICAL PROSTATECTOMY

The first radical prostatectomy was performed by the perineal approach in 1903 by Young [1], and the first retropubic approach described by Millin [2] in 1947. The current concept of retropubic radical nerve-sparing prostatectomy was established by Patrick Walsh et al. [3] in 1982. Novel approaches using laparoscopy were introduced starting in the 1990s, and the robotic approach in prostate surgery was introduced in originally in 2000 and at that time, only a few studies showed feasibility via a case report or series without clinical benefits [4-6]. The robotic approach has now been adopted exponentially since its introduction in 2000, when it was conceived as the Vattikuti Institute Prostatectomy (VIP) [7].

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Demonstrating a benefit in terms of perioperative outcomes reflected the initial experience with robotic prostatectomy at the VUI. Patients undergoing robot-assisted prostatectomy had shorter operating room times, lower estimated blood loss (EBL), lower complication rates, earlier urethral catheter removals, and a shorter hospital length of stay [8,9]. Functional outcomes in terms of continence and potency were also improved. These benefits were attributed to the surgical robot's 3-dimensional vision, high quality and intuitive controls, and high degree of freedom in instrument movements. Although oncological outcomes and positive surgical margin (PSM) rates are equivalent between robot-assisted radical prostatectomy (RARP) and radical retropubic prostatectomy (RRP), RARP may have a benefit in a long-term cancer-recurrence free survival rate in D'Amico-classification high-risk prostate cancer patients [10-12]. A systematic review by Ficarra et al. [13] revealed that functional outcomes were favorable in RARP over RRP. Most of all, the enhanced visualization and dexterity of the surgical robot have helped to reduce postoperative complication rates, as demonstrated in a series of 3,317 patients by Agarwal et al. [14] in 2011.

The surgical technique in robotic prostatectomy has evolved in many ways over the last 15 years. Initial surgical technique imitated a laparoscopic approach, which started posteriorly to dissect the seminal vesicles and vasa deferentia, followed by the bladder takedown to approach the bladder neck. It was not long before this posterior approach was supplanted by what we now think of as the VIP technique, wherein the prostate is approached anteriorly, starting with the bladder takedown, followed by the bladder neck, then dissection of the seminal vesicles and vasa deferentia. This change enabled the robotic approach to be applied on patient populations with higher body mass indices. Furthermore, progressive anatomic studies revealed that the neural tissue was not confined to a "neurovascular bundle," but rather spread over the wider surface of the prostatic fascia [15,16]. We hypothesized that the preserved neural tissue of the anterolateral aspects of the periprostatic fascial layer, which we named the, "Veil of Aphrodite," could potentially allow for greater nerve preservation [17]. We found that a bilateral "Veil of Aphrodite" technique used in men with localized prostate cancer and normal baseline erectile function resulted in better recovery of postoperative erectile function and a higher percentage of erections firm enough for intercourse at 12 months postoperatively, compared to men undergoing a standard bilateral nerve sparing technique [18].

Although a double-layered urethrovesical anastomosis (UVA)—consisting of posterior rhabdosphincteric reconstruction, as well as, lateral and anterior reconstruction—was expected to show an early return of urinary control, a randomized control trial in our institution demonstrated no advantages to double-layered UVA compared with single-layered UVA on early continence recovery or long-term continence rates [19-21]. However, double-layered UVA did show a significant decrease in cystographic leaks compared to single-layered UVA [22].

At the VUI in 2007, the urinary diversion for UVA has been done with the aid of a percutaneous suprapubic tube (SPT) instead of the conventional method of utilizing a urethral Foley catheter [23]. The benefits of the SPT are less catheter-related discomfort, decreased need for anticholinergic medications for bladder spasm related symptoms, and reduced risk of urethral or meatal strictures, without increasing the risk of bladder neck contractures [24].

The standard technique for the UVA was using a double-armed monocryl suture in a running fashion until the Food and Drug Administration (FDA) approved the polyglyconate-barbed suture for soft tissue approximation in 2010 [25]. The barbed suture reduced the anastomotic time by 26% without compromising outcomes, compared with the conventional monofilament suture.

Most recently the GelPOINT (Applied Medical, Rancho Santa Margarita, CA, USA) has been applied for our VIP technique along with renal surgery which will be described later, for real time bedside bimanual examination of the specimen, and for regional hypothermia by introducing ice slush, the Introcorporeal Cooling and Extraction (ICE) technique [26]. By applying the ICE technique with the use of the GelPOINT, and real time bimanual examination, the absolute risk of PSM in pT3a disease was reduced by 26.6%. The impact of regional hypothermia by cooling the neurovascular bundle is currently being evaluated as short-term outcomes were unclear.

RADICAL CYSTECTOMY

Radical cystectomy (RC) has been the gold standard of treatment for patients with muscle invasive bladder cancer, and now minimally invasive techniques have been adopted as the treatment of choice [27,28]. Robot-assisted radical cystectomy (RARC), as described by Menon et al. [29] in 2003, involved nerve sparing techniques adopted from the VIP method. The robotic approach has noted an early return of bowel function, decreased length of stay and lower estimated blood loss in the short term [30,31]. Nix et al. [32] published a prospective randomized controlled trial of RARC

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in 2010, with lymph node yield as a primary end point, and concluded that the robotic approach was non-inferior to the open approach.

A multi-institutional cohort database from the International Robotic Cystectomy Consortium (IRCC), with approximately 450 lymphadenectomies, revealed that the yield of lymph nodes retrieved between the robotic and open approaches were similar, obtaining an average of eighteen lymph nodes [33]. Davis et al. [34] reported a series in which the lymph node yield was forty-three, with an efficiency of 93%. On second look lymphadenectomy by the open approach, no residual lymphatic tissue was seen in 80% of the cases.

As we know, RC is associated with significant perioperative morbidity and mortality along with changes in the patient's quality of life. There have been a few series that have described a reduced rate of complications in patients who underwent RARC vs. open radical cystectomy (ORC) [31,32,35,36]. Specifically, Musch et al. [36] reported that patient's who underwent RARC experienced fewer postoperative adverse events of any Clavien-Dindo grade complication <90 days and <60 days after surgery, lower frequency of major complications, decreased estimated blood loss and transfusion requirement compared to the ORC arm. The lower risk of adverse perioperative outcomes with RARC would have potential benefits in the elderly population and has been shown to be a feasible treatment option in this age group (≥80 years old) with acceptable perioperative morbidity and short-term oncologic control [37]. Richards et al. [38] described in a single-institution prospective cohort study of 20 patients aged 75 years or older, there were fewer postoperative complications in those who underwent RARC, compared to those who underwent ORC. The RARC arm was an independent predictor of fewer overall and major adverse effects.

Khan et al. [39] reported the oncologic control of local disease in patients who underwent RARC after a follow-up period of 8 years were similar to the outcomes of patients who had ORC. Several other series and reviews have also demonstrated comparable oncologic outcomes between ORC and RARC [40-42]. However, RARC has the added benefit of offering a minimally invasive approach with smaller surgical incisions, which results in less postoperative pain and shorter hospital course. Albeit some of these studies were limited to a single surgeon or institution, these results should encourage a more robust, randomized controlled trial to ascertain select patients or institutions that can efficiently optimize these potential benefits.

In 2003, Menon et al. [29] published a pioneering RARC series of 17 cases. The 5- to 6-cm suprapubic incision, made for cystoprostatectomy specimen removal, was used to create an extracorporeal neobladder or ileal conduit. The created pouch was internalized, and the neo-vesicouretheral anastomosis was completed with robotic assistance after closure of incision. The initial RARC technique was developed with collaboration with Dr. Mohamed A. Ghoneim's group in Mansoura, Egypt, where the majority of urinary diversions were created using the W-pouch technique. The extracorporeal technique progressed into an intracoporeal technique with robot-assisted suturing dexterity as well as new advances in stapling devices. Multicentric IRCC data for 90-day postoperative follow-up has recently been published, comparing intracorporeal and extracorporeal urinary diversions, 167 vs. 768, respectively [43]. The operative time and median hospital stay were comparable, as were reoperation rates and complication rates. As expected with less bowel manipulation, gastrointestinal complications were significantly less in the intracorporeal group.

UPPER URINARY TRACT SURGERY

Partial nephrectomy (PN) is the gold standard treatment for small renal masses (SRMs). Compared to radical nephrectomy, PN has been shown to confer a survival advantage, similar oncologic outcomes, and minimizes the chance of severe chronic kidney disease in patients with associated renal dysfunction in the future [44-46]. Laparoscopic partial nephrectomy (LPN) is more commonly performed, has comparable oncologic control, less morbidity and shorter postoperative recovery period compared to open partial nephrectomy (OPN) [47]. However, LPN is more technically challenging, requires advanced surgical skills to achieve a negative tumor margin and to perform complex renal reconstruction, and has a steeper learning curve [48]. The advent of the robotic platform transformed the realm of upper tract surgery, and robot-assisted nephrectomies were performed starting in January 2004. With minimally invasive PN becoming the standard of care for renal tumors <4 cm in size, we published our initial experience of robot-assisted partial nephrectomy (RAPN) in 10 patients with mean tumor size of 2 cm [49]. In order to improve minimally invasive surgical skills, we devised novel laboratory models for solid renal tumor ("pseudotumor") and renal vein tumor thrombus ("pseudothrombus") in pigs and cadavers [50]. Techniques of RAPN were continuously refined and in 2009, we illustrated our four-arm technique of RAPN using a transperitoneal approach, highlighting the role of the fourth arm for renal hilar dissection, vascular control and during renorrhaphy [51]. The Tile-Pro feature of the da Vinci robotic system allowed visualization of intraoperative ultrasound and preoperative imaging study as a picture-on-picture image on the console screen to aid tumor margin identification [52]. Development of robotic bulldog clamps and intraoperative ultrasound probes gave further functional autonomy to the console surgeon by reducing his dependence on the variably skilled patient-side assistant [53,54]. The first report on the single-surgeon, single-center experience of RAPN for renal tumors was published from our institution, comparing T1a with larger tumors. We found equivalent EBL, total operative time, length of stay, complication rates and change in estimated glomerular filtration rate in the 2 groups [55]. Multi-institutional series later confirmed our results even for more complex tumors and in obese patients [56,57].

Various techniques for minimally invasive PN, like sliding clip renorrhaphy and early unclamping, appeared in an effort to reduce warm ischemia. Encouraged with the success of UVA with barbed suture during VIP, we established its safety and feasibility of a two-layered, running closure of the collecting system and renal capsule during renorrhaphy, and significantly lowering warm ischemia time (WIT) compared to the standard polyglactin suture (18.5 minutes vs. 24.7 minutes, respectively $p=0.008$) [58].

As regional hypothermia would expand the window for duration of permissible ischemia, we successfully experimented with the GelPOINT access platform to introduce ice-slush. With a mean cold ischemia time of 19.6 minutes and mean EBL of 296 mL, the technique of intracorporeal cooling was successfully used to achieve reproducible results [59].

Retroperitoneal access to the kidney obviates the need for bowel mobilization, and may reduce bowel related complications, pain management issues, as well as length of hospital stay. This approach will also confine blood and urine leaks to retroperitoneum, and may maximize the effectiveness of hypothermia techniques in the limited retroperitoneal space. Our recent description of robot-assisted retroperitoneal PN, which permits direct access to renal hilum for posterior and hilar tumors, is an effort in this direction [60]. A multicentric study by Hu et al. [61] showed retroperitoneal RAPN to have an acceptable morbidity and cancer control outcomes over a median follow-up of 2.7 years, proving retroperitoneal RAPN to be a reasonable alternative for patients with posterior renal masses or with prior abdominal surgery.

Recent trends show a resounding interest in the use of robot-assisted partial nephrectomy (RAPN) over LPN [62]. There are reported benefits and for some outcome measures, a superiority of RAPN over OPN and LPN [63-65]. The "trifecta" (which comprises a WIT<25 minutes, negative surgical margins and zero perioperative complications) has been used as a surrogate for quality of surgery in patients undergoing PN [63,66]. In a single-surgeon series of 500 patients, RAPN achieved the "trifecta" in almost 30% of the cases, with better operative outcomes and lower perioperative complications than compared to LPN [67]. RAPN is associated with a decreased length of stay, decreased intraoperative blood loss, and is less affected by the complexity of the renal tumor [68,69]. RAPN also offers a shorter WIT, which is a surrogate for final outcomes and achieves an overall better "trifecta" compared to LPN [66,70].

RAPN has a shorter learning curve than LPN and addresses some of the technical difficulties associated with the laparoscopic approach. Commonly cited advantages over LPN include a shorter learning curve with a wider range of indications, comparable or better operative, functional and oncologic outcomes, and better perioperative morbidity [48,63].

We described the feasibility of robot-asssited extended pyelolithotomy in 13 patients with staghorn calculi with a mean operative time of 158 minutes, mean console time 108 minutes, and EBL 100 mL, achieving stone free status in all but one patient [71]. Eun et al. [72] described a four-port "baseball diamond" strategy of port placement for patients undergoing nephroureterectomy to allow instrument access to the ipsilateral upper and lower urinary tract in the same operative session, without repositioning the patient and redocking the robot [72]. Utilizing the robotic magnification and precision in movement for micro dissection of anatomical planes around the adrenal gland, a four-step technique of robot-assisted right adrenalectomy and synchronous bilateral adrenalectomy were described [73,74].

NEWER FRONTIERS IN ROBOTICS SURGERY

The application of robot-assisted surgery continues to expand as technical improvements and surgeon experience continues to develop. Other notable areas where the robotic system are used include: pediatrics, solid organ transplant, endocrine and gastrointestinal surgery. Early experience has found robotic surgery to be a feasible option in renal, pancreatic, thyroid, gastrointestinal transplantation, and in gynecologic surgery [75-79].

The first robot-assisted living donor kidney transplantation (RAKT) was performed in 2000 [80]. Since then, numerous reports of good renal graft outcomes, perioperative outcomes

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and reduced morbidity and mortality have been published [81-83]. RAKT is particularly useful in obese patients and more appealing to would-be donors given the smaller surgical incisions, decreased postoperative pain, estimated blood loss, and shorter length of hospital stay. There is also decreased associated morbidity and mortality intra and postoperatively and better cosmesis [84,85]. In obese patients, RAKT reduces the risk of surgical site infection, which is very important for the transplanted graft and newly immunosuppressed recipient [86,87].

Robotic techniques are continuously getting refined and reestablished. Dr. Mani Menon originally modified the RARP as the VUI technique via a standard anterior approach in 2001. However, recently Bocciardi group from Italy and Rha group from South Korea have tried a posterior approach, retzius-sparing prostatectomy (RSP) [88,89]. Although the learning curve on perioperative outcomes, such as operating time and PSMs, were noted in their data, the RSP has potential benefits on the achievement on continence. The early experience of the RSP in our institution also showed similar outcomes of early return of urinary continence. With the use of the GelPOINT at our institution for immediate bimanual palpation, the initial learning curve for PSMs has reduced, although long-term oncological outcomes still need to be evaluated through a large prospective cohort or randomized controlled trial.

The robotic platform has even adopted into the pediatric population. In children with ureteropelvic junction obstruction, robot-assisted pyeloplasty is associated with significantly shorter length of stay, which directly correlates with decreased loss of parental wages and hospitalization cost [90-92]. The robotic approach enhances the laparoscopic technique, while maintaining the additional advantage of decreased pain, length of stay, rapid recuperation, and better long term cosmesis [93]. Robot-assisted laparoscopic ureteroureterostomy (RALUU) has been shown to be a viable option in patients with duplicated and single system ureters. This also results in operative times and complication rates comparable to the open approach. However, a slightly shorter hospital stay was observed in children who underwent RALUU [94].

THE FUTURE OF ROBOTIC SURGERY

Currently, Intuitive Surgical (Sunnyvale, CA, USA) is leading the market of robotic surgical systems, and 11 major companies are sharing the rest of the market. According to the report from the Wintergreen Research Company, robotic surgical systems collectively markets at $3.4 billion in 2014 are anticipated to reach up to $20 billion by 2021. New surgical robotic systems will continue to approach the market, but the leaders in robotic surgical system will still be Intuitive Surgical's da Vinci surgical system. As of December 2015, 3597 da Vinci surgical systems were installed in the world.

The da Vinci surgical system was approved for a cardiac surgery in 1999 by the FDA and applied for prostate cancer in 2000. The application of da Vinci system has since been extended within the urologic field to include the kidney, bladder, reconstructive urologic surgery, and even to kidney transplantation. Evolution of robotic approach might expand its boundary toward new techniques to replace the established open and laparoscopic surgical techniques, or its indication from localized tumor to the locally advanced disease.

Initially, the idea of a robot-assisted surgical system was driven by the Navy and designed to enable a surgeon to perform tele-surgery. However, this has not been possible since the master and slave systems are connected through signals travelling close to light speed, and the delay between the movements of a surgeon and the machine increases with longer distance.

CONCLUSIONS

Minimally invasive surgical techniques have been expanding the boundary of application on urologic surgeries, because of the decreasing rate of perioperative outcomes and similar oncological results. Due to intuitive movements with advanced wrist movements, 3-dimensional vision and surgeon's ergonomics, the robotic surgical technique has replaced the laparoscopic technique in many urological applications. Robotic surgery continues to evolve into newer techniques and refine the past techniques.

The market growth and the competition of newer surgical systems should translate to improvement of surgical technique and clinical outcomes.

CONFLICTS OF INTEREST

The authors have nothing to disclose.

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