REVIEW ARTICLE

Robotics in urological surgery: Evolution, current status and future perspectives

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Abstract
Context: Robotic surgery is rapidly evolving and has become an essential part of surgical practice in several parts of the world. Robotic technology will expand globally and most of the surgeons around the world will have access to surgical robots in the future. It is essential that we are updated about the outcomes of robot assisted surgeries which will allow everyone to develop an unbiased opinion on the clinical utility of this innovation.

Objective: In this review we aim to present the evolution, objective evaluation of clinical outcomes and future perspectives of robot assisted urologic surgeries.

Acquisition of evidence: A systematic literature review of clinical outcomes of robotic urologic surgeries was made in the PUBMED. Randomized control trials, cohort studies and review articles were included. Moreover, a detailed search in the web based search engine was made to acquire information on evolution and evolving technologies in robotics.

Synthesis of evidence: The present evidence suggests that the clinical outcomes of the robot assisted urologic surgeries are comparable to the conventional open surgical and laparoscopic results and are associated with fewer complications. However, long term results are not available for all the common robotic urologic surgeries. There are plenty of novel developments in robotics to be available for clinical use in the future.

Conclusion: Robotic urologic surgery will continue to evolve in the future. We should continue to critically analyze whether the advances in technology and the higher cost eventually translates to improved overall surgical performance and outcomes.

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La robótica en la cirugía urológica: evolución, estado actual y perspectivas futuras

Resumen

Contexto: La cirugía robótica evoluciona rápidamente y se ha convertido en una parte esencial de la práctica quirúrgica en diversas partes del mundo. En el futuro la tecnología robótica se expandirá globalmente y la mayoría de los cirujanos en todo el mundo tendrán acceso a robots quirúrgicos. Es fundamental que nos mantengamos al día en cuanto a los resultados de los procedimientos quirúrgicos asistidos por robots, lo que permitirá a todos desarrollar una opinión imparcial sobre la utilidad clínica de esta innovación.

Objetivo: El objetivo de esta revisión es presentar la evolución, una evaluación objetiva de los resultados clínicos y las perspectivas futuras de las cirugías urológicas asistidas por robot.

Adquisición de la evidencia: Se llevó a cabo una revisión bibliográfica sistemática de los resultados clínicos de las cirugías urológicas robóticas en PubMed. Se incluyeron ensayos controlados aleatorios, estudios de cohortes y revisiones de artículos. Además, se realizó una búsqueda detallada en el buscador de la web para obtener información sobre la evolución y las tecnologías en desarrollo en robótica.

Síntesis de la evidencia: La evidencia actual sugiere que los resultados clínicos de las cirugías urológicas asistidas por robot son comparables a los resultados de cirugías convencionales abiertas y laparoscópicas, y se asocian con menos complicaciones. Sin embargo, no se dispone de resultados a largo plazo de todas las cirugías urológicas robóticas comunes. Son muchos los desarrollos innovadores en robótica que estarán disponibles para el uso clínico en un futuro cercano.

Conclusión: La cirugía urológica robótica continuará evolucionando en el futuro. Deberíamos seguir analizando críticamente si los avances en tecnología y el mayor coste se traducen finalmente en un mejor rendimiento quirúrgico global y en mejores resultados.

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Introduction

The application of robotic technology in clinical practice took place over the last few decades. Though the initial application of robotics in medicine was highly diverse, the major impact of this fascinating technology was in the assistance of minimally invasive surgeries. Robotic surgery has escalated the future prospects of minimal access surgery and has helped surgeons to overcome some of the major limitations of conventional laparoscopy. Robot-assisted surgeries have evolved a long way from being merely a technological marvel with surgeons’ and patients’ intrigue for technology to being an integral part of surgical practice with distinct advantages. Robotic assistance in medical interventions as we know today will only grow proportionally and there will be a point where most of the surgeons around the world will have access to this amazing technology. The future developments in robotic surgery are profoundly limited to human imagination and can potentially escalate to unimaginable heights. In this review, we aim to present the evolution, objective evaluation of clinical outcomes, and future perspectives of robot-assisted urologic surgeries.

Acquisition of evidence

A systematic literature review of clinical outcomes of robotic urological surgeries was made in PUBMED. Randomized control trials, cohort studies, and review articles were included. Moreover, a detailed search in the web-based search engine was made to acquire information on evolution and evolving technologies in robotics.

Synthesis of evidence

Evolution of robotics in urology

The word ‘ROBOT’ (robota in Czech meaning forced labor) was first coined by Karel Capek (1921) in his play Rossom’s Universal Robots. 1

The present-day surgical robot is an outcome of evolution in two distinct technologies – telemanipulation and minimally invasive surgery.

Telemanipulation or telepresence, human operated master slave manipulation from a remote location, was primarily used for working in dangerous or hazardous conditions like handling radioactive material, exploring deep sea, outer space etc. In the mid 1980s, significant advances in computing and electronics resulted in major advances in robotics. The first crossover of robotic technology and medical intervention took place in 1985 with Kwok et al. performing a neurosurgical biopsy with great precision using a robot – Puma 560. This system later evolved into PROBOT, a robot to perform transurethral resections of the prostate. 2 But these robots were elementary models designed to perform menial and repetitive tasks.

Meanwhile, French physician Philippe Mouret performed the first laparoscopic cholecystectomy in 1987. 3 Following this milestone surgery, there was an intense boom in the
popularity of laparoscopic surgery. But soon laparoscopy reached a plateau and was restricted to simple surgical procedures due to its limitations. Loss of 3 dimensional (D) visualization, compromised dexterity and limited degree of motion, fulcrum effect, and amplification of physiological tremors compelled surgeons to seek versatile alternatives.

Also in the late 1980s, the National Air and Space Administration (NASA) Ames Research Center in joined collaboration with the Stanford Research Institute (SRI) developed a dexterous telemanipulator for hand surgery. The United States (US) Army, impressed with the SRI project, funded the development of Mobile Advanced Surgical Hospital (MASH) for surgeons to remotely operate on wounded soldiers in war zones to reduce the time to reach the medical facility. Several surgeons and engineers working in the army project further formed a commercial venture leading to introduction of robots to civilian surgical community. Automated Endoscopic System for Optimal Positioning (AESOP), a robotic arm controlled by voice commands to employ an endoscopic camera resulted from this civilian project. Computer Motion and Integrated Surgical Systems (now Intuitive Surgical) further progressed with extensive research to introduce the present-day robots – Zeus and Da Vinci surgical systems respectively. The landmark ‘Lindbergh operation’ – transcontinental robot-assisted laparoscopic cholecystectomy was performed with Zeus surgical system in 2001. Advanced robotic surgical systems equipped with 3D high definition visualization, improved dexterity, seven degree of freedom, ergonomic position, elimination of tremors, ability to scale motions overcame the limitations of conventional laparoscopy and was readily accepted by the surgical community.

In urology, robots were explored in several sections. The first urology experience with telerobotic procedure was SR 8438 Sankyo Scara robot (1995) used for precise integration of ultrasound monitoring and targeting transperineal prostate biopsy. ABLATHERM, robot developed to accurately deliver High Intensity Focused Ultrasound for prostate cancer was developed by Albert Gelet, Lyon, France. LARS robot developed by John Hopkins University was used to assist surgeons in percutaneous renal access. A further development of this tool led to PAKY (Percutaneous Access to the Kidney) device with success rate of 87%.

Most significant impact of robotics in urology is that of the Da Vinci surgical system for assisted laparoscopic surgeries. Binder et al., Frankfurt, Germany (2000) performed the first Da Vinci-assisted radical prostatectomy which was later published by Abbou in 2003. Later, Mani Menon from Henry Ford Hospital, Detroit with limited laparoscopic experience and mentored by Vallancien G, Institute Montsouris, Paris, France further refined the technique of robot-assisted prostatectomy reducing the operative time, blood loss, and morbidity. Menon’s experience led the foundation for widespread use of robots in urological surgery.

Intuitive surgical further refined surgical robots with the recently Food and Drug Administration (FDA) approved fourth generation prototype – Da Vinci Xi. Fourth generation Da Vinci robots are equipped with overhead arm architecture, improved vision, thinner arms, and longer instrument shafts enabling anatomical access to virtually any position.

Current status of robotics in urological surgery

Surgical techniques requiring microsurgical precision, advanced reconstructive skill, and inaccessible operative fields can be optimized with robotic surgery. The urologic surgeries commonly performed with robots are radical prostatectomy, radical cystectomy, and partial nephrectomy.

Robot assisted radical prostatectomy (RARP)

Radical prostatectomy is one of the early urological surgeries performed with a robot and is the most common robotic urologic surgery so far. Now with 10 years of experience, we must critically analyze whether the increased cost and technical comfort offered by the robots have translated into fewer complications and improved oncologic outcomes.

The overall reported complication rate following RARP is 5–7% of Clavien 1 and 2 and 4% of Clavien 3 and 4 complications. Mortality rates are consistently rare (0.1–0.2%) following RARP. A systematic analysis by Novara et al. comparing RARP with Laparoscopic Radical Prostatectomy (LRP) and Open Radical Prostatectomy (ORP) have shown that blood loss, transfusion rates, and hospital stay are lower in RARP. Tewari et al. performed a systematic review and meta-analysis of peri-operative outcomes following RARP and showed that the readmission rates, reoperation, ureteral/rectal injury, deep vein thrombosis, pneumonia, hematoma, lymphocele, anastomotic leak, fistula, and wound infection are significantly lower in RARP.

The positive surgical margin following RARP is noted in 9–15% of the patients and was similar to LRP and ORP. Surgeon’s experience appears to be an important predictor of PSM. Diaz et al. reported the 10-year follow-up data following RARP and showed the biochemical recurrence occurred in 22.4% of patients, and actuarial Bio-Chemical Recurrence Free Survival (BCRFS), Metastasis Free Survival (MFS), and Cancer Specific Survival (CSS) rates at 10 years were 73.1%, 97.5%, and 98.8%, respectively. These results were comparable to contemporary ORP cohorts. D’Amico risk groups or pathologic Gleason grade, stage, and margins were the strongest predictors of BCR.

Ficarra et al. reported 12-month pad-free continence rates ranges from 69% to 96%, and if a relaxed definition of no pad or security pad was used, the rates were 89–92%. They also showed a statistically significant advantage in favor of RARP over LRP and ORP in terms of 12-month urinary continence recovery. Age, Body Mass Index (BMI), comorbidities, urinary symptoms, and prostate volume are predictors of urinary incontinence after RARP. Twelve month and 24 month potency rates following RARP were 54–90% and from 63% to 94%, respectively. The predictors of potency recovery following RARP were age, baseline potency status, comorbidities, and nerve-sparing procedure. They also reported a statistically significant faster 12-month potency recovery in RARP than in ORP.

There is clear evidence to show that the outcomes of RARP improve with surgeon’s experience. These are the long-term results of cases performed during the early part of the learning of robotic surgery. The vast improvements in the
robotic technology, instruments, and surgeon’s versatility will further enhance the outcomes of RARP.

**Robot-assisted partial nephrectomy (RAPN)**

Robot-assisted partial nephrectomy was developed only in recent years with potentially promising improved surgical outcomes. RAPN is largely restricted to high-volume academic centers. Improved dexterity of the robotic instruments, freedom of movements with 3D high-definition magnified vision allows the surgeon to overcome the limitations of conventional laparoscopy and perform complex resections. The literature published on the outcomes of RAPN is limited. The peri-operative outcomes of RAPN analyzed in US multi-center study of 886 patients demonstrated the feasibility of RAPN with comparable complication to Open Partial Nephrectomy (OPN). Intra-operative and post-operative complications reported in the study were 2.6% and 13% respectively, 3.6% of the observed complications being Clavien grade 3 and 4. Median Warm Ischemia Time (WIT) was 18.8 min with Estimated Blood Loss (EBL) of 100 ml. The prevalence of positive surgical margin was 2.2%, 16,17 Khalief et al. reported 3-year and 5-year follow-up data on the oncologic outcomes following RAPN. The overall survival was 97% at 3 years and 90% at 5 years with recurrence-free survival at 3 years and 5 years of 98.92% and 98.92%, respectively. And the cancer-specific survival was 99.04%. 18

Kaczmarek et al. evaluated the perioperative and functional outcomes of 66 patients who underwent a RAPN without hilar clamping and observed that off clamp surgery resulted in more blood loss and smaller decrease in renal function.19 Several authors have reported the feasibility of RAPN in larger tumors and complex hilar tumors with prolonged operative time, high EBL and WIT.20 Few small series have reported the utility of RAPN in special situations like solitary kidney, multiple tumors, recurrent tumors, and associated chronic renal disease.21 But these surgeries were performed by experienced surgeons in academic institutions.

A prospective, multicenter study comparing Laparoscopic Partial Nephrectomy (LPN) and RAPN by Masson-Lecomte et al. showed significant advantages in favor of RAPN in terms of WIT, operative duration, operating room occupation time, EBL, use of hemostatic agents, and length of stay. Another comparative study by Khalifeh et al. in 261 patients treated with RAPN and 231 treated with LPN demonstrated the overall trifecta rates (WIT<25 min, negative surgical margins, and no perioperative complications) of 58.7% in RAPN and 31.6% in LPN groups.21,22 These data of RAPN are from the early clinical experience. RAPN can potentially become an alternative to traditional OPN.

**Robot-assisted radical cystectomy**

Rapid adoption of robot-assisted surgeries in the various sections of urology intrigued the urologist to perform robot-assisted radical cystectomy (RARC). First RARC was performed in 2003 and later spread to limited academic institutions across the world. The International Robotic Cystectomy Consortium (IRCC) formed in 2006 provides most of the database on RARC.

Hayn et al. demonstrated that RARC requires a steep learning curve and an estimate that 21 cases were needed to achieve an operative time of 390 min and 30 patients were required to get lymph-node yield (LNY) of 20 and also to attain 5% positive surgical margin rate. Moreover, previous RARP experience can decrease EBL and improve LNY.12 The consolidated data from IRCC have reported a positive surgical margin of 6.8% in RARC, which is comparable to the contemporary Open Radical Cystectomy (ORC) (1–10%). And the lymphadenectomy in RARC is comparable to ORC with 83% of patients having more than 10 nodes removed. Overall complication rates following RARC is as high as 48%, with 19% being Clavien grade 3–5 and mortality in 4.2% of patients. Age and receipt of blood transfusion were predictors of 90-day morbidity and mortality.23 Several authors have reported the feasibility of robotic intracorporeal urinary diversion.14

**Other robotic urological surgeries**

Centers experienced in robotic surgeries extended the clinical application to other minimally invasive urological surgeries. Pyeloplasty, ureteral reimplantation, appendicovesicostomy, and augmentation enterocystoplasty are increasingly being performed with robot assistance. Long-term outcomes will define the role of the robot in these surgeries.

Table 1 summarizes the long-term clinical outcomes of the common robot-assisted urological surgeries.

**Robotics in other specialities**

Robotic technology shows an interesting progress in other surgical specialities. Robotic-assisted laparoscopic procedures including hysterectomy, myomectomy, radical hysterectomy, pelvic and aortic lymphadenectomy, trachelectomy, parametrectomy, tubal anastomosis, sacrocolpopexy, and others are the gynecological procedures reported in the literature.25 Robotic surgery was also embraced by pediatric surgeons over the past decade with more than 2300 procedures reported in 1840 patients. The most prevalent procedures performed were fundoplication, pyeloplasty, and lobectomy.26 Cardiac valve surgeries, coronary bypass, and lung resections are being performed with robotic assistance with the advantage of less blood loss, shorter hospital stay, reduced pain, and lower complications.21,23 Da Vinci Surgical System has revolutionized the surgical management of thyroid diseases with superior cosmesis attained through retro-auricular or trans-axillary incisions.29 Trans-oral robotic surgery (TORS) provides access to the oropharynx, hypopharynx, larynx, oral cavity, parapharyngeal space, and skull base via the oral aperture. This makes it possible to perform complex resections with minimal scar, reduced surgical morbidity, and improved outcomes.32 Robotic application in spine surgery has achieved a convincing favor in a short time span due to its potential for higher surgical accuracy and better outcomes with fewer complications.32
Future of robotic urology

Robotic technology was readily embraced by the surgeons because of its versatility and properties that overcame the limitations of conventional laparoscopy. Novel robotic platforms, downsizing the hardware and flexible instruments are being evaluated to further improve the robotic surgery experience and broaden the application (Table 2).

The Surgeon’s Operating Force-feedback Interface Eindhoven (Sofie) robot from the Netherlands is an innovative portable robot that incorporates haptic feedback allowing the surgeon to sense the force applied by the instruments.33 Amadeus (Titan Medical Inc, Toronto, Ontario, Canada) will be the next commercially available multi-arm robot with vision tower, a surgical cockpit, and the patient-side robotic arms cart.34

Retrofitted robotic instruments are being embedded by light emitting diode (LED) to detect tissue oxygenation and ischemia similar to pulse oximeter and provide imaging feedback to the surgeon.35 Robotic arms integrated with wide range of power sources for cutting and stapling combined with flexibility and precision will be available in the future. Intra-operative nerve mapping system will aid in easy identification of invisible nerves and to effectively perform nerve-sparing procedures.

Feasibility of incorporating robot to single-site surgery and Laparo-Endoscopic Single-Site surgery (LESS) has been reported in several urological procedures.36 Hyper-redundant snake-like arm and spider arms will enable Robotic LESS to be more feasible. Researchers have proposed a unique miniature in vivo robot to be incorporated in Natural Orifice Transluminal Endoscopic Surgery (NOTES). But this marvelous technology is still a dream at present.37 Another emerging trend is a hand-held robot which is smaller in size and completely under-grounded and manipulated by the surgeon in the free space.

The real-time fusion of imaging-like ultrasound, computed tomography, and magnetic resonance imaging (MRI) during a robotic surgery will be a reality with the availability of 'Stealth Station' and MRI compatible robotic arms. This technology will provide the surgeons in a robotic console with real-time image of the organs and the abnormal areas within, and help in deciding appropriate surgical planes.38

Robot models are being developed for endoscopic surgeries where a dexterous manipulator robot arm can be introduced into a resectoscope sheath and used for identifying bladder tumor, resections using lasers, and for surveillance.39 There are reports of transperineal robotic prostate biopsy to precisely localize the tumor for further application in focal therapy.40 With the availability of MRI compatible robotic arms and the ability for the real-time fusion of various imaging technology (MRI, spectroscopy, histoscaning, etc.), robot-assisted prostate biopsy can be a reality in the near future with superior systematic sampling. This idea can be further applied to focal therapy like ABLATHERM, cryotherapy. It is plausible to imagine a real-time monitoring of the therapy with continuous imaging and precisely controlling the target areas and also to decide the endpoints of therapy.

Conclusion

Robotic surgery as we know it today represents only the infancy to how much technology will advance in the future. The developments will ease the surgical experience for the surgeons and the patients and also improve the surgical outcomes. We will see more of image fusion, gene coding, nanotechnology in the future and extension of robots beyond minimally invasive surgeries. We should also critically analyze if the improvement in technology and the cost results in improved overall performance. As we realize now that the idea of robotic surgery is no more a fiction, we will very soon see today’s imaginations as a reality in the near future.
Conflict of interest

The authors declare that they have no conflict of interest.

References


