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TOPIC PAPER

Advances in robotic surgery for pediatric ureteropelvic junction obstruction and vesicoureteral reflux: history, present, and future

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Abstract

Purpose The introduction of robotic surgical technology into urological reconstruction, particularly pediatrics, has introduced new horizons for reducing the morbidity and enhancing the efficacy of surgical repair of congenital conditions in children. In reviewing the evolution of pediatric urological applications of robotic surgery, we wanted to address the different levels of reported utilization of pyeloplasty and ureteral reimplantation as two of the most common procedures.
Methods Review of the published literature sought to explore the described variation in clinical application of these two common procedures, and the evolution of the practice over time.
Results Reported outcomes suggest that variations in patient selection, the learning curve and in reporting of outcomes all contribute to the wide variation in utilization of pediatric robotic pyeloplasty and ureteral reimplantation.
Conclusions These technologies are demonstrating their potential as well as the challenges of use in children and there is a steady evolution of capability. Practitioners should be aware of both the possibilities as well as the risks of such new technology in the care of our patients. This requires thorough and open reporting of outcomes, the willingness to introduce change and integrate new findings into practice.

Keywords Robotic surgery · Pediatric · Urology · Pyeloplasty · Ureteral reimplantation

Introduction

Pediatric surgery has significantly advanced in the last 2 decades, primarily due to the advancement of techniques in minimally invasive surgery (MIS). The application of laparoscopy has taken time to be adopted due to the steep learning curve and need for efficiency among surgeons. Since the mid-2000s, robotic surgery has become a mainstay in adult urology to facilitate the learning curve previously associated with laparoscopic surgery, and has expanded in pediatric urology [1]. The robot has well-known significant advantages intraoperatively, including providing high-resolution three-dimensional visualization, tremor-filtered instrument control, and comparable manual dexterity to open surgery [1]. Patients can have reduced incisional length with higher satisfaction of scar appearance, quality of life, shorter hospital stays, and more rapid recovery [1, 2].

Pediatric urology in the United States has expanded use of the robot, particularly in management of ureteropelvic junction obstruction (UPJO) and vesicoureteral reflux (VUR). Both of these surgeries require precision in dissection and reconstruction, which are ideal cases for a robotic-assisted approach. Surgical management of UPJO is the most widely performed and best described robotic procedure to date [2]. The role of the robotic-assisted laparoscopic pyeloplasty has since become commonly applied to pediatric patients, with continued expansion of surgical technique, notably in infant populations [1, 3]. Conversely, there remains equivocal data on the role of robotic surgery in management of vesicoureteral reflux, mostly based on surgeon experience and the learning curve associated with performing robotic-assisted ureteral reimplantation [4]. Why is it then, that robotic pyeloplasty has been adopted as a standard of care, while ureteral reimplantation has yet to see similar application in the robotic approach? We seek to provide a perspective on (1) the progressive history of robotic surgery, particularly in its applications for UPJO and VUR; (2) the

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status of how these pediatric conditions are treated today, with optimizing the operating room team and fine-tuning both the technique and art of MIS; and (3) where the pediatric urologist and the operating room will stand with robotic surgery in the future.

History of pediatric robotic surgery: reviewing the robot's uses in pyeloplasty and reimplantation

The rise of the robot

Rodney A. Brooks, the former director of the Massachusetts Institute of Technology Artificial Intelligence Laboratory stated in his book, Flesh and Machines: How Robots Will Change Us, "while human surgeons are still in charge, sometimes for good reason, and sometimes just for historical reasons, they are being augmented with computer vision and robotic aids." The role of the surgeon in the rapidly advancing surgical world has continued to be fluid in how to best treat a patient with more precision and efficiency. To understand the evolution of robotic surgery, one must recall the early experiences of laparoscopic surgery and its applications in common conditions treated among pediatric urologists, notably UPJO and VUR.

Laparoscopy was first used diagnostically in 1976 in an 18-year-old male to identify an intra-abdominal testis [5]. Laparoscopy continued to expand steadily among pediatric surgeons due to its advantages as a minimally invasive approach with improved cosmesis [2]. It was not until 1992, however, when the first laparoscopic nephrectomy was performed in a child by Kavoussi et al. taking approximately 5.6 h of operative time, with use of a morcellator on the specimen prior to removal [6] that complex laparoscopic procedures in pediatric urology began to emerge. While laparoscopic surgery has been well established in its fundamental uses for MIS, efficacy and decreased morbidity, robotic "master–slave devices" were being developed as early as the 1980s. One of the earliest drivers of robotic-assisted surgery was the military, where remote surgical care was explored for injured soldiers in hazardous locations [7].

The automated endoscopic system for optical positioning (AESOP) robot system was an early robot prototype developed by Computer Motion (Goleta, CA, USA). This system functioned as a camera holder controlled by the surgeon as well as a robotic arm that could be controlled manually or by remote control. The AESOP system allowed the surgeon to no longer need a human camera assistant [8]. Newer generations of AESOP included voice control to minimize use of a foot pedal [9]. Although the AESOP provided improved visual control in MIS, there was still need for improved dexterity of instruments for more delicate manipulation of tissues [10].

The Da Vinci robot developed by Intuitive Surgical (Sunnyvale, CA, USA), was first introduced in 1988, initially to be used by cardiac surgeons to provide additional manual dexterity in addition to improved visualization with a three-dimensional (3D) immersion console [10, 11]. The Zeus system, developed by Computer Motion (Goleta, CA, USA), was introduced at nearly the same time as the Da Vinci system with a more flexible mounting system that attached to the operating room table, but less robust manual controls and visualization. The Zeus platform all but disappeared as Computer Motion was acquired by Intuitive and the Da Vinci system became the only FDA-approved surgical robot available today [10, 11].

Adaptation of the robot to UPJO and VUR

In 1995, the first reported pediatric laparoscopic pyeloplasty was accomplished successfully, laying the groundwork for future advances in pediatric urologic reconstructive surgery [12]. General application of laparoscopic pyeloplasty in children was very limited, however, until the Da Vinci system became available in 2002. Since then, robotic pyeloplasty has become the most commonly performed robotic procedure in pediatric urology. Reported success rates of 95% were comparable to those of open pyeloplasty. Additionally, the robotic needle drivers were able to delicately reconstruct the collecting system, using material such as 6-0 or 7-0 suture in a manner similar to open pyeloplasty [1, 7, 13–15]. During the early years of robotic pyeloplasty between 2004 and 2006, whether retroperitoneal or transperitoneal, patients had either similar or longer surgical times, but overall shorter hospitalization compared to open pyeloplasty [11]. In the mid to late 2000s, most pediatric urologists were familiar with using 8 mm and 12 mm ports, with few reporting the use of 5 mm ports on the Da Vinci system [1, 10, 11], primarily in the general surgery fields for fundoplication, and in urology for pyeloplasty [10]. Most pediatric surgeons used the 12 mm endoscopic camera for three-dimensional views, however, based on the size of a child, a 5 mm monocular endoscope was also available [10]. The key advantage of the robot system discussed in the mid 2000s was the advancement in reconstructive surgery with more precise suturing and vascular control [11]. As advancements in robotic surgery continued and more adult and pediatric urologists applied MIS techniques to other conventionally open surgeries, the robot provided the toolbox necessary to adapt well-established techniques in a novel manner.

Robotic surgery for vesicoureteral reflux (VUR) has had a more complicated and challenging history, primarily due to variation in surgical technique and clinical outcomes [10]. Laparoscopic ureteral reimplantation was attempted relatively early in the emergence of pediatric reconstructive laparoscopy, but was even less widely used for many years [16–19]. Conceptually, the extravesical reimplantation was straightforward, but the surgical angles and need for precision during development of the detrusor tunnel was more difficult to master; early results were not very positive in contrast to pyeloplasty [20]. Similarly, laparoscopic intravesical ureteral reimplantation was explored and in a few hands was successful and efficient, it was used in only a limited number of centers [21, 22]. With the introduction of the Da Vinci system, however, the needed dexterity to efficiently perform ureteral mobilization, tunnel creation and suture closure was more readily accomplished [23]. Similarly, intravesical access was possible, although still challenging in children with large port sizes. While the extravesical surgery continued at a slow and steady pace, there was very limited use of the intravesical method [11]. The principle limitations were seen as the challenge of developing and maintaining intravesical insufflation as well as the need for closure of the large bladder port sites.

The extravesical robotic approach has been reported on in large numbers with variable success that is below the expected success of open surgery. As a result, the utility of this approach relative to open or endoscopic methods has been vigorously debated. The reasons for the variability remain incompletely defined, but may include significant variation in technique, patient selection, outcome parameters, and surgeon experience. Attempts to identify key determinants have not yielded specific factors. The reports demonstrating high levels of success in large numbers of patients with rigorous outcomes assessment suggest that the technique is viable, however, these results need to be more generalizable, and several groups have published multi-centered outcomes, albeit with variable techniques [24]. In the context of an ongoing evolution of the indications for anti-reflux surgery, variable success rates, uncertain morbidity reduction in younger patients, and inherent technical challenges, robotic ureteral reimplantation is unlikely to approach the level of utilization of pediatric pyeloplasty anytime soon. With a focus on greater standardization of patient selection, surgical technique and consistent postoperative assessment, robotic ureteral reimplantation should become a valuable part of our surgical armamentarium.

The present: where we stand now on robotic pyeloplasty and reimplantation

Comparing today's approaches to UPJO and VUR

Robotic pyeloplasty is a standard of care for older and larger children, nearing 100% reported success rates in resolution of clinical symptoms and radiographic indicators of obstruction [2]. It is now considered to be the most commonly performed robotic procedure among pediatric patients, although the overall numbers of pyeloplasties in children have decreased [25]. Selected patients can undergo concurrent robotic pyelolithotomy for stone removal [2]. In one of the largest multicenter comparison studies of robotic compared to laparoscopic pyeloplasty, patients had shorter length of stay and lower postoperative complications [26]. United States-based national analyses of robotic pyeloplasty determined it to be more expensive than open pyeloplasty but similar to the cost of laparoscopic pyeloplasty [15]. Most analyses comparing robotic versus open pyeloplasty appear to be based on operative time to assess proficiency and surgical skill; the overall operative time can be skewed based on complexity of individual cases, and the skillset of the operative team [27]. However, the cost-to-benefit balance of robotic compared to open pyeloplasty remains equivocal, largely due to the need for additional operating room staffing and equipment [25]. The fairly clear reduction in postoperative morbidity in older children continues to drive its use and it is likely that with further improvements in instruments and greater standardization of operative technique, robotic pyeloplasty will continue to be a mainstay of pediatric urology.

Although the gold standard for correction of VUR remains open ureteral reimplantation, robotic ureteral reimplantation is on the rise [7]. Robotic ureteral reimplant rose from less than 1% in 2000–2012 to over 6% in 2016 [2, 4, 15]. While the intravesical and extravesical approaches have been well described, much of the outcomes depend on surgeon experience [2, 7]. Intravesical robotic reimplantation has not been as robust in recent years, possibly due to the technical challenges posed and limited workspace associated with working in an insufflated bladder [23, 28]. The extravesical approach is more widely accepted, although with a range of success rates from 72 to 99%, possibly due to the variability of surgical practices and experience [7, 28], its utility is unclear. In one multi-institutional study of children undergoing extravesical robotic ureteral reimplantation, surgical success (resolution of reflux, prevention of reoperation), was only 72%; however, this study only included a population of 61 patients with 91 ureteral units [29].

Overall surgical indications for VUR have declined recently, notably since the revised American Academy of Pediatrics Guideline did not routinely recommend a voiding cystourethrogram at the time of an initial UTI [23]. Moreover, the concurrent use of endoscopic management of VUR may have contributed to some of the equivocal acceptance of attempting to standardize robotic ureteral reimplantation. In a study comparing open ureteral reimplantation, robotic ureteral reimplantation, and endoscopic injection of bulking agents (Deflux), Harel et al. noted VUR resolution rate of 100%, 85%, and 78.4%, respectively. It should be noted that this study included 93 patients who underwent open reimplantation, 76 who underwent Deflux, and only 14 who underwent robotic reimplantation [23]. Ultimately, the robotic-assisted management of VUR continues to be compared in small case series and retrospective reviews, with varying degrees of approaches and surgeon experience. Compared to the standard and widely accepted practices of robotic-assisted pyeloplasty, robotic-assisted ureteral reimplantation requires continued analysis of surgical outcomes with rigorous postoperative assessment.

Facing current roadblocks in robotics: limitations of the robot or of man?

As robotic surgery becomes more customized to pediatric populations, most urologists are becoming more cognizant of the physiologic and anatomic differences in children compared to adults. Studies have noted the need for caution due to the smaller working environment, more compliant abdominal walls of children, abdominal location of the bladder, more sensitive decreases in cardiac output and development of crepitus [7]. Finklestein et al. noted the increased length of time required for setup of an infant when less than 15 kg [3]. Due to increased gastric emptying, children are more likely to develop small bowel distension compared to adults, thereby obscuring intraperitoneal approaches to urologic surgery [2]. None of these issues are inherent limitations to pediatric application of robotic surgery, however.

Even today, the robot should be seen to be in its early developmental stages in pediatric urology; there yet remains the question as to whether robotic surgery can be considered safer and more effective than conventional laparoscopic surgery. Most reviews indicated that orchiopexies may not be as useful to be performed robotically due to the surgeon not needing precise suturing, in comparison to laparoscopic or open orchiopexy [10, 11, 14]. The articulation of the 5 mm instruments are different from the 8 mm counterparts, creating a larger radius of articulation and making fine-tuned movements difficult in smaller spaces [30]. Prior to the mid 2010s, it was difficult to ascertain whether definitive assessments could be made on robotic surgery as a whole in pediatric urologic patients; most reported uses on the robot were preliminary case series and techniques were still in evolution. The balance of efficiency and cost-effectiveness were still being determined before the onset of more simulation, training, and standardized approaches to credential surgeons on the robot [13].

Since the learning curve amongst laparoscopic surgeons was steep in its early stages, the advance of the surgical robot provided a more ergonomic approach to minimally invasive surgery [27]. In a recent study, 62% of participants who underwent the FLS training model found robotic suturing preferable to pure laparoscopic intracorporeal suturing; only 10% of these individuals had sufficient robotic experience [15]. This correlates with the adaptability of the robot to the delicate suturing required in a pyeloplasty, while lessening the steep learning curve associated with MIS. However, the robot continues to be a complex system to learn to use safely and effectively today [13]. Proper function of the robot, optimal operative timing, and patient outcomes go beyond just the skill of the surgeon. Robotic surgery, such as laparoscopic surgery, is a team effort. Members of the operating room staff must have awareness and standardized training on the functionality of the robot for troubleshooting, a competent and well-trained bedside assistant, and knowledge of how positioning can affect both physiology of the patient and functionality of the surgical system [1, 13]. Continuing to promote a cohesive team dynamic when performing robotic surgery will optimize both surgical and patient outcomes in pediatric patients.

Future implications of the surgical robot: beyond the pyeloplasty

There is much to consider when looking towards the future of robotic surgery in pediatric urology. Clearly, specific interventions, such as ureteral reimplantation, have room for optimizing surgical instruments, standardization of techniques, and understanding patient selection among surgeons and trainees. We feel there is more opportunity in the surgical indications of robotic ureteral reimplantation, notably in older or larger children diagnosed with VUR. At this time, there is an open horizon to the applications of the surgical robot in pediatric minimally invasive surgery, particularly in the setting of oncology. Although rare, one could consider partial or heminephrectomy or retroperitoneal lymph node dissections in a robotic approach, more so for older or larger children. When considering the possibility of furthering extracorporeal MIS, one can even consider robotic hypospadias surgery as well as fascial and skin closures to gain the advantages of magnification, instrument stabilization and precise movements [31].

Reviews have noted that not all pediatric hospitals have access to a robotic suite [2]. Given that most high-volume robotic centers tend to be tertiary care centers or academic institutions, more emphasis needs to be placed on surgical training on the robot. Having the opportunity to consistently repeat a certain procedure, notably robotic pyeloplasty, can optimize both patient and financial value of a robotic surgical program [15]. When considering a globalized approach to implementing robotic surgery [29], pediatric urologists need consensus on providing more concrete guidelines for surgical steps, similar to how the Society of Urologic Robotic Surgery has published recommendations for robotic-assisted laparoscopic prostatectomy (RALP) [15]. As standardization of specific cases continues, there is also room to consider the role for machine learning of well-established procedures. The robot could be given additional programming to recognize important surgical landmarks to aid the surgeon, and trainees, in being more precise and safe in robotic surgery. These considerations could further solidify training of residents and fellows. Sorensen et al. noted that one should perform 15–20 cases of a robotic pyeloplasty before one has similar outcomes to a concurrent open pyeloplasty [32], however, a review by Murthy et al. notes that one should perform 100 cases for consistent outcomes on the robot [15]. None of these guidelines has been validated in any substantive way, however. The question remains, by whom and how should these "training" cases be proctored, particularly in cases that are still being adapted to the robot?

While the wide reach of pediatric robotic surgery in both geographic and treatment modalities expands, the cost of maintaining a robotic suite, operating room staff, and continued medical education should decrease from a societal perspective [2]. Each case should involve the precise decision-making in surgical indications, adherence to known technical principles, and streamlined postoperative management. Many early reports upon which we base our perspective of pediatric robotic surgery for UPJO and VUR are based on highly selected patients; not all children have clear indications for surgery. As such, the adoption of robotic surgery in applications of known pediatric urologic conditions should also be carefully selected based on the patient, the surgeon's experience, and the accessibility of a competent minimally invasive surgical team. As we look towards the horizon of advancing the technical elements of the surgical robot, we should continue to look back on the evolution of pediatric urology, from the reconstructive nuances that individual thought and creativity provides, to the evidence-based standard approaches of fundamental surgical steps.

Conclusions

Based on the last 2 decades it is clear that the surgical robot has become and will continue to be a mainstay in pediatric urology, in particular for treatment of UPJO. The role of the robot in management of VUR is more so dependent upon the age and size of the patient, and the experience level of the surgeon in considering the various approaches to perform a ureteral reimplantation. The contrasting evolution of these two fundamental pediatric urologic procedures highlights the role of various factors that define surgical evolution. To be able to advance a technology, whether a telephone or a computer, human thought and experience are required. The robot still relies on direct human manipulation, both with the individual surgeon and the surgical team, working to improve operative safety and efficiency. These advances are for the betterment of our patients and their families, and we should continue to share experiences on a global level to best improve successful patient outcomes.

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