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UROLOGY (MICHAEL PHELAN, SECTION EDITOR)

Robotics in Pediatric Urology- History, Evolution, and Future Directions

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Abstract

Purpose of Review Robotic-assisted laparoscopic surgery (RALS) has revolutionized pediatric urology over the last two decades. This review will detail the history and evolution of urologic pediatric robotic surgery from a global perspective and discuss the ways in which this unique surgical platform continues to grow.

Recent Findings Numerous outcome studies have been performed to compare postoperative complications of robotic-assisted surgery to its laparoscopic and open counterparts, with promising results. Still, the cost efficacy, training, and dissemination of such new techniques remain a challenge. Further, there are unique opportunities to continue to advance the field with new technology including 3D printing and fluorescent imaging.

Summary The integration of RALS into pediatric urology has advanced minimally invasive care across multiple surgical procedures, and continues to gain traction internationally. This technology is still in its youth as future iterations will continue to provide added benefits to patients, surgeons and medical institutions.

Keywords Robotic surgery · Pediatric robotic surgery · Pediatric urology · Robotic-assisted laparoscopic surgery · Training · Da Vinci

Abbreviations

RALS	Robotic-assisted laparoscopic surgery
RALP	Robotic-assisted laparoscopic pyeloplasty
OR	Operating room
PRM	Pediatric robotic mini-fellowship
ICG	Indocyanine green

Introduction

As the practice of medicine trends toward more minimally invasive treatments, robotic surgery has rapidly gained traction within the pediatric urology community. At the turn of the century, the first robotic-assisted laparoscopic surgeries (RALS) within the field were performed, and less than two decades later, many became the treatment of choice and even redefined the new standard of care. Patient benefits of robotic surgery include improved cosmesis, shortened postoperative hospital stay, and shortened recovery time [1]. Surgeon benefits of robotic surgery include a magnified 3D view, tremor filtration, improved operator ergonomics, and improved range of motion [2]. Numerous outcome studies have been performed to compare post-operative complications of robotic-assisted surgery to its laparoscopic and open counterparts, with promising results. However, even with these improvements, the cost efficacy, training, and dissemination of such new technology remain a challenge.

This review will detail the history and evolution of urologic pediatric robotic surgery from a global perspective and discuss the ways in which this unique surgical platform will continue to grow in the future.

History and Evolution

Urology has always been at the forefront of medical technological advances. The introduction of laparoscopic surgery within pediatric urology in the 1980s laid the groundwork for robotic surgery. Though laparoscopic surgery was first used diagnostically in 1976 for the identification of intra-abdominal testes, it soon continued to disseminate throughout the field and was used for the first pediatric nephrectomy in 1992 and pediatric pyeloplasty in 1995 [3]. However,

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robotic systems further pushed the envelope of minimally invasive surgery by overcoming the challenges that laparoscopic surgery posed such as restricted maneuverability, limited visualization, and a steep learning curve. [3]

Since its approval for human use in 1999, the da Vinci robot created by Intuitive Surgical (Sunnyvale, CA, USA) has revolutionized numerous adult surgeries within cardiothoracic, oncologic (ie. head and neck cancers), gynecologic, and urologic settings [4]. Within urology, robotic surgery was first widely adopted for prostatectomies [5, 6] and was soon applied to a variety of other procedures including pyeloplasty, nephrectomy, adrenalectomy, cystectomy, vasectomy reversal, and pyelolithotomy, among others [7]. However, it was not until the early 2000s that these urologic robotic surgeries were performed within the pediatric population.

The robotic-assisted laparoscopic pyeloplasty (RALP) for the treatment of ureteropelvic junction obstructions was one of the earliest procedures that was detailed in a series of case reports from 2002 onwards [8–11]. Interestingly, by 2015, an estimated 40% of all pediatric pyeloplasties were performed robotically [12, 13]. After the initial success of RALP, pediatric urologists began to apply the da Vinci system in ureteral implantations for the treatment of vesicoureteral reflux [14]. Indeed, among the pediatric robotic surgery literature, both pyeloplasty and ureteral implantation are the most commonly described procedures [15, 16]. The first robotic-assisted pediatric Mitrofanoff was performed in 2004 [1, 17], shortly followed by the first robotic pediatric Malone antegrade continence enema reported in 2008 [18]. More recently, there is increasing literature on pediatric radical and partial nephrectomy, pediatric bladder augmentation (first performed in 2008), bladder neck reconstruction, Mitrofanoff appendicovesicostomy, and Malone antegrade continence enema [19•]. Outcomes of the aforementioned procedures will be discussed below. Even newer procedures under consideration for RALS, utilized in select patients, include kidney stone treatment, renal mass removal, and oncologic lymph node dissection [1]. Today, as RALS continues to progress, the feasibility and efficacy of the robot is being explored in the infant population [20]. However, further studies will aid in elucidating the role of the robot in the management of such patients.

Not only have the procedures deemed suitable for RALS evolved, the robot surgical system itself has also advanced. Since the original prototype in 1999, the da Vinci surgical platform has undergone multiple generations of updates including a transition from 2D to 3D high definition view, increased surgical “arms” for additional surgical instrumentations, and a dual console for a second operator [21]. The most recent rendition, released in 2014, is the da Vinci Xi [21]. Additional robot development is also underway to allow for robot-assisted laparoendoscopic single port surgery, but this has yet to be used in the pediatric setting [12]. Finally, robot models other than the da Vinci are being established globally, with Italy, Korea, the United Kingdom, Singapore, and Germany cultivating systems that are under various phases of development and commercial use. [12]

RALS procedures were initially embraced in North America, with progressive global uptake [15, 22]. A bibliometric analysis by Cundy et al., found that as of 2016, over 75% of the pediatric RALS publication volume was attributed to the United States [15]. Still, the analysis found that 48 institutions from 16 different countries had participated in the pediatric RALS literature [15]. In recent years, there has been a deliberate development of training programs for RALS, both country-specific [23] as well as international workshops [24, 25•]. The concept of international mini-fellowships such as the University of Chicago Pediatric Robotic Mini-fellowship (PRM) and workshops has proven successful and continues to garner international interest in RALS. Many surgeons who participate in such programs assist in bringing RALS to their home institution [25•]. Still, the steep costs of purchasing and maintaining robotic equipment, as well as the lack of training infrastructure, are persistent barriers in implementing RALS in lower and middle income countries. [26, 27]

Since the advent of robotic-assisted surgery within pediatric urology over two decades ago, the estimated yearly case volume has increased an average of 240% per year [15]. While this growth does not match the pace of adult urologic RALS, robots continue to revolutionize pediatric urologic surgery.

Present Day Outcomes (vs. 15 years Ago)

There is growing evidence that usage of RALS has led to favorable surgical outcomes for various types of robotic-assisted procedures over the past several years compared to its inception.

One of the first reports of robotic-assisted laparoscopic pyeloplasty (RALP) in children was published in 2005 [9]. Since then, RALP has become the most common robotic-assisted urologic surgery performed in children. Numerous case series have shown that RALP resulted in comparable or more favorable outcomes than alternative approaches [24, 28, 29]. With similar or shorter lengths of postoperative hospital stay and similar success rates between RALP and open and/or laparoscopic approaches, RALP may be utilized as the universal approach for management of ureteropelvic junction obstruction in pediatric patients (Table 1). [30•, 3231 and]

For other pediatric urologic procedures that have been performed robotically, such as ureteral reimplantation [33–38], appendicovesicostomy [39–45], and Malone antegrade continence enema (MACE) [39, 46, 47], recent case series have continued to support favorable outcomes for robotic-assisted surgeries compared to the traditional open approach. Since the initial case reports of successful robotic surgery in the mid to late 2000s, various single surgeon case series, multi-institutional studies, and meta-analyses have emerged and have provided robust outcome data showing the safety and efficacy of these robotic approaches. Similarly, relatively limited literature on robotic partial nephrectomy has also shown favorable outcomes for robotic-assisted surgery with regards to length of postoperative hospital stay and postoperative complication rates (Tables 2, 3, 4, 5 and 6). [48–51]

As the field continues to expand and benefit more children, one must also give special consideration to the patient's age, size and weight. Though the development of 5 mm instruments has allowed for robotic procedures to be performed on patients with a smaller body habitus [52], there

Table 1 Summary of robotic pyeloplasty primary outcomes

Author(s)	Year published	N of robotic patients	Success rate (robotic)	Postoperative complication rate (robotic)
Minnillo et al	2011	155	96%	11%
Singh et al	2012	34	97%	9%
Atug et al	2005	7	86%	0%
Murthy and Gundeti et al	2015	52	94%	13%
Song et al	2017	10	100%	10%
Cohen et al	2021	100	98%	6%
Silay et al	2019	26	100%	7.70%
Chan et al	2017	633	–	2.10%
Kawal et al	2018	104	96%	30.8% (median)

Table 2 Summary of robotic hemi nephrectomy primary outcomes

Author(s)	Year published	N of robotic patients	Success rate (robotic)	Postoperative complication rate (robotic)
Lee et al	2009	9	100%	22%
Mason et al	2014	21	–	9.50%
Malik and Gundeti et al	2015	16	–	13%
Neheman et al	2018	18	–	–
Ballouhey et al	2017	15	–	13%

Table 3 Summary of robotic ureteral reimplantation primary outcomes

Author(s)	Year published	N of robotic patients	Success rate (robotic)	Postoperative complication rate (robotic)
Peters and Woo	2004	6	83%	17%
Smith et al	2011	25	97%	–
Marchini et al	2011	39	No difference (data not shown)	10% (intravesical); 6% (extravesical)
Schomburg et al	2014	20	100%	10%
Gundeti et al	2016	58	82%	0%
Boysen and Gundeti et al	2017	260	87.90%	9.60%
Boysen and Gundeti et al	2018	143	93.80%	7.10%
Esposito et al	2021	1362	92%	10.70%
Neheman et al	2019	27	–	9%

Table 4 Summary of robotic appendicovesicostomy primary outcomes

Author(s)	Year published	N of robotic patients	Success rate (robotic)	Postoperative complication rate (robotic)
Pedraza et al	2004	1	100%	0%
Storm et al	2007	3	100%	0%
Nguyen et al	2009	10	–	15%
Wille and Gundeti et al	2010	11	–	55%
Famakinwa and Gundeti et al	2013	18	94.40%	39%
Gundeti et al	2016	88	85.20%	29.50%
Grimsby et al	2015	39	–	26%
Galansky and Gundeti et al.*	2021	35	91.20%	38.20%
Juul et al	2022	5	80%	40%

*Outcomes in Galansky and Gundeti et al. (2021) are for combined catheterizable channel procedures (APV, MACE)

Table 5 Summary of robotic bladder neck reconstruction primary outcomes

Author(s)	Year published	N of robotic patients	Success rate (robotic)	Postoperative complication rate (robotic)
Bagrodia and Gargollo	2011	4	100%	0%
Gargollo	2015	38	82%	16%
Grimsby et al	2016	19	58%	16%

Table 6 Summary of robotic Malone antegrade continence enema primary outcomes

Author(s)	Year published	N of robotic patients	Success rate (robotic)	Postoperative complication rate (robotic)
Lendvay et al	2008	1	100%	0%
Thakre et al	2008	1	100%	0%
Zee et al	2017	1	100%	–
Halleran et al	2018	7	86%	29%
Galansky and Gundeti et al.*	2021	11	91.20%	38.20%
Saoud and Gundeti et al	2022	13	84.60%	23.10%

*Outcomes in Galansky and Gundeti et al. (2021) are for combined catheterizable channel procedures (APV, MACE)

was mixed evidence regarding its utility as such instruments improved cosmesis but did not affect outcomes resulting in product termination [53]. Studies have demonstrated that weight is not an absolute contraindication to robotic surgery [54]. While there may be challenges presented to the surgeon such as limited space and the need for alternative trocar placements, lighter and smaller patients did not experience greater complications [55]. Current reports are promising and suggests that robotic procedures can be safely performed in patients weighing less than 10 kg. [56, 57] There is also a growing body of literature demonstrating the feasibility, safety, and success of robotic surgeries in a younger cohort, namely infants (defined as < 1 year of age). Infant robotic surgeries within urology were comparable to its open and laparoscopic counterparts [58, 59]. Further, in comparison to an older cohort (> 1 year of age), infant RALP yielded no significant differences in length of hospital stay, complication rates, or success rates. [60]

While favorable results have been achieved in infant robotic surgery, additional research is necessary to confirm the benefits of utilizing this technology for the younger pediatric population [61]. Infant-focused adaptions in surgical technique are necessary. Of note, infants have physiologic and anatomic differences that yield unique challenges requiring special consideration from an experienced RAL surgeon and the accompanying anesthesia team on anesthetic effects, pneumoperitoneal and intracranial pressure, and safe insufflation and end tidal CO2 [53]. Finkelstein et al. put forth the first set of patient size parameters to help aid in the patient selection criteria for robotic surgery, suggesting that an anterior superior iliac spine and AQpuboxyphoid distance measurement of 13 and 15 cm or less, respectively, may restrict surgical ability due to collisions [62]- although, this suggestion can be confounded by the presence of pneumoperitoneum [53]. Additionally, as the general body of RAL surgical expertise has grown, tips and tricks to overcome the size limitations in infant RAL surgery have been proposed. For instance, simple adjustments such as patient positioning, port triangulation, and careful manipulation of robot arms can help maximize working space [53]. As RAL technology further evolves, targeted pediatric-specific RAL innovations and training will aid in a more widespread adoption among the infant population.

There is a robust and continuously growing body of literature that has reported promising data on robotic surgery outcomes through a wide range of pediatric urologic procedures since the initial reports of these procedures in the mid 2000s. However, one limitation remains the lack of standardization of outcomes tracked and reported between case series. Clearer study protocols would allow for increased multi-institutional study, larger case series, and easier meta-analyses of results. Another limitation remains the lack of randomized controlled trials in the current body of literature, as the large majority of outcome studies have been retrospective analyses. Moreover, while robotic surgeries have shown either better or non-inferior outcomes across multiple categories, some additional concerns remain the inevitable increased operative times of robotic surgeries in addition to the increased cost of these surgeries compared to their open counterparts [63, 64]. Nonetheless, with increased training and availability of new technology, we expect a continuous decrease in both operative times and costs with this evolving surgical modality. [65]

Future of Robotics in Pediatric Urology

Technology

In recent years, the field of minimally invasive surgical systems has continued to grow and major advances in robotic surgery continue to be innovated. Current urologic robotic platforms have stable magnified 3D views for the robot operator, which greatly assists in intracorporeal suturing [2]. However, the surgical assistants working by the patient only have access to a screen with a two-dimensional (2D) view of the surgical field. While the use of 3D vision for surgical assistants has not been studied in the context of pediatric urologic surgery, it is worthy of further investigation as it could increase assistant comfort and efficiency [66]. In certain scenarios, 3D view could also be utilized in resident training as well as pre- and intra-operative planning [67, 68]. The role of 3D printing has also been discussed in aiding with training and education, and has experienced exponential growth in recent years with a large impact. 3D printed models may be used as pre-operative planning tools for practicing surgeons, as procedural models for hands-on practice, or as models for patient education and counseling [69–74]. The role of both 3D images and 3D printing and their intersection with virtual reality in pediatric urologic robotic surgery remains a novel area to be explored.

Additionally, Firefly™ Fluorescence Imaging can be integrated with the da Vinci™ robotic surgical system to further optimize robotic procedures [75]. The Firefly™ technology utilizes fluorescent imaging to help the surgeon evaluate the vascular perfusion of anatomic structures and work in a magnified 3D field, assisting with the identification of healthy tissue and normal versus malignant tissue. This addition to the robotic platform makes it well-equipped for technically demanding procedures such as the major reconstruction of the bladder and urinary tract, and for oncologic robotic procedures such as robotic partial nephrectomy. The near-infrared (NIRF) dye indocyanine green (ICG) is often the dye used for fluorescence-guided surgery and serves as the main focus of most commercial fluorescence-guided surgery cameras [76, 77]. In urologic surgery, initial reports have shown this technology as safe and effective, although larger studies with longer follow-ups are needed [78]. While usage of ICG is relatively well-established in adult surgery, its usage remains sparse in pediatric surgery [79]. A systematic review by Le-Nguyen et al. in 2021 showed increasing use of ICG in pediatric surgical specialties, allowing us to speculate that this emerging technology may soon be one of the future technical developments in pediatric robotic urology. [80]

Lastly, with the rapid advent of the 5G system, artificial intelligence, and digital platform of surgery over the past decade, the landscape of robotic surgery will be continuously evolving. It is hypothesized that robotic operations performed from a remote position to limit the needs for travel will be a possibility in the future [81]. These advancements will be crucial in a post-COVID pandemic era to help facilitate the care of patients in need in times of potential travel bans/regulations.

Learning and Training

With the growing use of robotic systems in the surgical community, there has been a call for the development of training curricula and validated assessment tools of proficiency [82]. Prior reports have discussed factors relating to the initiation and maintenance of a successful pediatric robotic urology program [83]. Additionally, the impact and outcomes of the University of Chicago PRM mini-fellowships and surgery workshops appear successful and promising for continued support [24, 25•]. Andolfi et al. demonstrated the successful implementation of a 5-day pediatric robotic mini-fellowship (PRM) [25•]. With a combination of tutorials, hands-on inanimate and animate skills training, clinical case observations, and video discussions, they showed that an intensive PRM appeared to help postgraduate surgeons successfully incorporate robotics into their following practice.

Looking into the future, the continued implementation of virtual reality (VR) and augmented reality (AR) simulation can help address the learning curve of robotic surgery [84]. A systematic review that was published by Schmidt et al. in 2021 showed that technical skills acquired through robotic VR simulation training can be translated into the operating room (OR), and that OR performance may be predicted by robotic VR performance [85]. This is in line with prior evidence of skill transfer from laparoscopic VR simulators to the OR [86]. Overall, increased investment in VR robotic simulators and expansion of simulation in training curricula may ultimately lead to shortened operating times, reduced costs, and/or improved surgical decision-making.

Cost and Availability

Despite the advantages of the robotic platform, we are currently limited due to the cost constraints of equipment across the world. Although there are some mixed reports, [65] the current consensus is that robotic-assisted procedures cost more than the equivalent open procedures [63, 64]. However, given that many of these studies were conducted during the learning phase of surgeons, we expect overall costs of surgeries to continually decrease as surgeons gain greater experience, especially with the onset of new technology and standardized training programs as discussed above. Furthermore, financial analysis of hospital stay expenses, pain medication costs, and OR times is complex and multifaceted. When considering these cost-comparison studies, it is essential to consider the downstream effects of implementing robotic equipment on revenue and costs. While usage of robotics may necessitate an increased initial investment in purchasing of equipment, the consequent effects on revenue are unforeseen and need to be considered in future cost analysis. With the continuous growth of disruptive technology that is transforming the landscape of robotic surgery, we hope that these new pathways will soon be available at a reasonable cost so that children in need can benefit.

Conclusion

The impressive growth of RALS within pediatric urology can be appreciated over the last three decades. Though it has rapidly evolved, the future of robotic surgery within pediatric urology, and across the globe, remains bright. RALS is now the future platform for digital surgery, and continues to hold potential to revolutionize minimally invasive surgery.

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Declarations

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Recently published papers of particular interest have been highlighted as:
- • Of importance
- •• Of major importance

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