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Review

Robotic surgery in pediatric urology

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Abstract While robotic surgery has shown clear utility and advantages in the adult population, its role in pediatrics remains controversial. Pediatric-sized robotic instruments and equipment are not readily available yet, so certain modifications can be made in order to make robotic surgery successful in children. While the cost of robotic surgery remains high compared to open procedures, patients experience greater satisfaction and quality of life with robotic surgery. Robotic pyeloplasty is a standard of care in older children, and has even been performed in infants and re-do surgery. Other robotic procedures performed in children include heminephroureterectomy, ureteroureterostomy, ureteral reimplantation, urachal cyst excision, bladder diverticulectomy, and bladder reconstructive procedures such as augmentation, appendicovesicostomy, antegrade continence enema, bladder neck reconstruction and sling, as well as other procedures. Robotic surgery has also been used in oncologic cases such as partial nephrectomy and retroperitoneal lymph node dissection. Future improvements in technology with production of pediatric-sized robotic instruments, along with increases in robotic-trained pediatric urologists and surgeon experience along each's learning curve, will help to further advance the field of robotic surgery in pediatric urology.

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1. Introduction

Minimally invasive surgery has become more widely accepted in pediatric urology. Laparoscopy was first employed in 1976 to identify an intraabdominal testes in an 18-year-old male [1]. The first infant laparoscopic nephrectomy was performed in 1992 by Koyle et al. [2] for a right multicystic dysplastic kidney identified *in utero*; the operative time was under 1 h and the patient recovered well. Robotic-assisted laparoscopic surgery was widely accepted in adult urology due to improved visualization (10—15 times magnification power and three-dimensional images), improved range of motion with 90° articulation of the robotic arms with seven degrees of freedom (compared to four in conventional laparoscopy) and motion scaling, along with elimination of hand tremor. This led to shorter hospital stays, decreased narcotic usage, decreased blood loss, with smaller scars and improved cosmesis. In children, the advent of better robotic instrumentation has led to its greater use for many common surgeries and its expansion in more complex procedures.

1.1. Troubleshooting robotic surgery for pediatric patients

In pediatric urology the benefits of robotics remains controversial. Many pediatric surgical facilities lack access to a robot, mainly due to cost but there is a lack of published high-level evidence of its benefits in children spurring critics to demand additional proof of its efficacy. Some of the challenges faced in performing robotics surgery in children is the loss of haptic feedback and limited instrumentation for and trocars suited for children [3]. Children have unique physiologic and anatomic differences compared to adults that increases the complexity of minimally invasive surgery. These limitations include more rapid gastric emptying times which leads to increased small bowel distention and subsequent compromise of access and visualization, the bladder is located in a more abdominal position, and the increased abdominal wall laxity creates higher risk for vascular or bowel injury during access. In order to overcome these challenges, various tricks can be employed such as using a "baby bump" (rolled up egg crate cushions) to position the smaller patient, marking the robotic ports after insufflation to adjust for the abdominal wall laxity, moving the robotic arm to a more linear and less triangulated position due to the smaller working space, using the open Hasson technique for peritoneal access, intussusception of the trocars during placement to avoid vascular or bowel injury, and anchoring the trocars to the skin with stitches to prevent dislodgement. Insufflation pressures are age-dependent: 0—2 years, 8—10 mmHg; 2—10 years, 10—12 mmHg; 10—18 years, 12—15 mmHg. Also, the use of the AirSeal® device is advantageous in keeping pneumoperitoneum when an assistant port is needed. Among a cohort of 858 patients, Clavien grade I, II, III, and IV complication rates of 6.9%, 8.2%, 4.8%, and 0.1%, respectively, were noted of which 1.6% required conversion to open or pure laparoscopic procedures, and 86% of these were due to mechanical malfunctions in the robot [4].

Despite size differences in children robotic surgery has been performed successfully in small infants. Ballouhey et al. [5] found that operative times, hospital stay, and postoperative outcomes were similar in children greater than or less than 15 kg, with only longer robotic set-up times for patients less than 15 kg, and Finkelstein et al. [6] found that at least a 13 cm distance between anterior superior iliac spines (for lower urinary tract procedures) and at least a 15 cm puboxyphoid (for upper urinary tract procedures) can aid in selecting infants for robotic surgery.

1.2. Robotic cost and patient satisfaction

The cost associated with robotic surgery is an often cited detractor of acceptance. Indirect costs (robot and console, annual service fees, operating room renovations and investments) seem to be the main contributor to total expense, while direct costs (operative room expenses, anesthesia, room and board, *etc.*) can be lower than the equivalent open procedure [7]. Mahida et al. [8] found the total cost of admission was higher following robotic procedures than non-robotic procedures for both pediatric urologic ($14 583 *vs.* $9388) and general surgery ($13 954 *vs.* $10 180) cases. Tedesco et al. [9] noted that 349 robotic cases needed to be performed annually at their institution to offset the added cost. Nevertheless, as the field of robotic surgery in pediatrics continues to grow and facilities purchase robotic equipment with increased usage, expenses should decrease and the robotic will become a more affordable treatment modality. Implementation of robotics into surgical training programs, along with formalized education, workshops, and robotic simulators all contribute to surgeon experience and efficiency of the learning curve with robotic surgery. Construction of robotic surgery programs in hospitals with dedicated robotic nursing staff, pediatric anesthesiologists familiar with the physiologic alterations associated with robotic-assisted laparoscopic surgery, and supportive administration will help to improve the robot's efficiency and thus its costs.

Patients have expressed improved satisfaction with robotic surgery. Parents of children who underwent robotic pyeloplasty reported significantly higher satisfaction with overall life, confidence, self-esteem, postoperative care, and scar size compared to open pyeloplasty in a validated survey [10]. As the size of the incision grows with the patient, the improved cosmesis that accompanies minimally-invasive surgery becomes arguably one of the most important factors in the pediatric population.

2. Surgeries

2.1. Pyeloplasty

Robotic pyeloplasty for treatment of ureteropelvic junction obstruction is the pioneer procedure of pediatric robotic surgery, and has been documented in literature since the turn of the millennium. The procedure is now a standard of care for older or larger children and data from some of the higher quality studies are shown in Table 1. Thorough description of the transperitoneal technique was documented by Peters [11]. For port placement, a

Table 1 Review of robotic pyeloplasty in children.

Author	No. of patients	Mean age (year)	Operative indication	Surgical approach	Operative ports	Mean operative time (min)	Hospital stay (day)	Complications	Mean follow-up (week)	Success rate (%)
Olsen et al., 2007 [19]	65	7.9	Pain (37), decreased function (5), infection (5), increased pelvic anteroposterior diameter (5), combination of above (13)	Retroperitoneal	4 (12 mm camera, 2 × 8 mm operative, 5 mm assistant)	146	2	UTI (2), transient hematuria (2), displaced catheter (3), temporary nephrostomy (4)	52.6	100
Sorensen et al., 2011 [13]	33	9.2	Pain (19), prenatal hydronephrosis (8), stones/UTI (4), other (2)	Retroperitoneal	3 (12 mm camera, 2 × 8 mm operative)	326	2.2	Gross hematuria (1), anastamotic leak (4)	69.5	97
Barbosa et al., 2013 [14]	58 (10 bilateral)	7.2	Pain, increased hydronephrosis and renal function below 40%	Transperitoneal	Not described	Not described	Not described	Redo pyeloplasty for persistent hydronephrosis (1)	143.4	62.1 resolved hydronephrosis and 25.3 improved
Subotic et al., 2011 [15]	19 (2 bilateral)	All >4, mean age not given	Increased or severe hydronephrosis, and differential renal function <45%, functional loss of more than 10%, recurrent UTI	Transperitoneal	4 (12 mm umbilical, 2 × 5 mm operative, 5 mm assistant)	165	6	Port site hernia-omentum (1), macrohematuria (1), dislodged stent (1), UTI (2), anastomotic leakage (1)	26.1	100
Kutikov et al., 2006 [18]	9	0.47	Ureteropelvic junction obstruction	Transperitoneal	3 (camera, 2 × 5 mm operative)	122.8	1.4	None reported	Not described	78
Avery et al., 2015 [17]	60 (2 bilateral)	0.61	Hydronephrosis (30), worsening renal function (16), UTI (6), failure to resolve (4), other (4)	Transperitoneal	4 (8.5 or 12 mm umbilical, 2 × 5–8 mm operative, ±5 mm assistant)	232	1	Port site hernia (2), UTI (1), urine leak (1), retained stent (1), postoperative renal calculus (1), prolonged ileus (1)	52.1	91
Asensio et al., 2015 [20]	5	10.59	Reoperative repair following failed pyeloplasty	Transperitoneal	4 (12 mm camera, 2 × 8 mm operative, 5 mm assistant)	144	2.6	None reported	105.9	100

UTI, urinary tract infection.

10 mm camera port is placed in the umbilicus, an 8 mm working port is placed in the superior midline at least one hand width away from the camera, and the inferior 8 mm working port is placed either in the midline for smaller children or slightly lateral for triangulation in larger children. An assistant port is placed midway between the camera and working port on the contralateral side of the abdomen through which suction can be used and sutures passed into the field. This approach has the advantage of easier identification of a secondary obstruction, such as a crossing accessory renal vessel, along with superior suturing capability with ureteropelvic junction reconstruction performed in either running or interrupted fashions. The renal pelvis can be accessed by either reflecting the colon or by creating a window in the mesentery. A concomitant robotic pyelolithotomy can be performed in the presence of stones [12]. A ureteral stent can be placed in the antegrade fashion either through the assistant port or via an angiocatheter placed through the abdominal wall. The learning curve was described by Sorensen et al. [13] who determined that performing 15 to 20 cases of robotic pyeloplasty was necessary to achieve operative times and surgical outcomes similar to those of the open procedure. Studies comparing robotic to open pyeloplasty have documented a decreased length of hospital stay and decreased use of pain medication; however, robotic surgeries are associated with longer operative times. Long-term operative outcomes demonstrate higher levels of complete resolution of hydronephrosis (62% *vs.* 45%) and decreased median time to improvement (12.3 months *vs.* 29.9 months) when compared with conventional open pyeloplasty [14]. When compared to pure laparoscopic pyeloplasty, robotic-assisted cases achieve similar success rates with decreased complications and postoperative hydronephrosis. Very rarely do conversions to open surgery or reoperation for obstruction occur [15]. Casella et al. [16] found robotic pyeloplasty offered shorter operative times (200 min *vs.* 265 min) without significant differences in total costs ($15 337 *vs.* $16 067) compared to laparoscopic pyeloplasty.

Robotic surgery can be offered in infants with severe ureteropelvic junction obstruction. Avery et al. [17] reported on 60 patients with a mean age of 7.3 months resulting in 91% improvement or resolution of hydronephrosis, 11% complication rate, and two patients requiring reoperation. Kutikov et al. [18] reported similar success in a series with nine 3–8-month-old (mean 5.6 months) infants who underwent transperitoneal robotic pyeloplasty with good outcomes.

The retroperitoneal approach to a pyeloplasty can be achieved robotically, with the first series reported by Olsen et al. [19] in 2004 involving 13 children, with ages ranging 3.5–16.2 years (median age of 6.7 years), who underwent 15 pyeloplasties with follow-up of 1–7 months with good outcomes. They later reported a larger series involving 67 pyeloplasties in 65 patients with 5 years follow-up, featuring a complication rate of 17.9%, with only one patient requiring conversion to open surgery and with four patients requiring reoperation. They concluded that the retroperitoneoscopic approach involved a shorter operative time and produced comparative results.

Reoperative robotic pyeloplasty has been reported as well with 100% success and 0% complication rates in some series [20], deeming this approach safe and effective for recurrent ureteropelvic junction obstruction. For extreme cases when there is a paucity of healthy renal pelvic tissue, robotic ureterocalicostomy can be performed successfully [21].

2.2. Partial nephrectomy and nephroureterectomy

Simple nephrectomy for benign disease such as atrophic kidneys, multicystic dysplastic kidney disease, and renovascular hypertension, can be performed robotically in children; however, these cases can be performed quite easily with conventional laparoscopy. The robot has been employed when performing bilateral procedures, such as nephrectomy with contralateral ureteral reimplantation with mean operative times of 291 min, estimated blood loss of 16 mL, hospital stay of 2.3 days, and good imaging outcomes at follow-up [22]. The robot has also been used to perform nephroureterectomy for nonfunctional renal units and occasionally can be performed without having to redock the robot as newer robotic designs include a flexible robotic arm and a circulating base for the arms. A review of 24 robotic nephroureterectomy cases with patients median age of 51.6 months and weight of 16.9 kg gave median operative times of 227 min, hospital stay 2 days, morphine-equivalent narcotic use of 0.03 mg/kg/day, and an 8.3% complication rate (urinary retention and a urine leak at ureteral stump, both managed by urinary catheter placement) [23]. The port placement for these combined retroperitoneal and pelvic procedures were similar to that described in pyeloplasty, except the assistant port is placed between the camera and inferior working port. If the robot is to be re-docked, the camera port remains the same, and the assistant port is now used as a working port, and the superior working port becomes the assistant port.

Lee et al. [24] showed the safety and feasibility of robotic hemi-nephrectomy in nine patients with a mean age of 7.2 years, operative time of 275 min, estimated blood loss of 49 mL, and hospital stay of 2.9 days. One patient required percutaneous drainage of an asymptomatic urinoma, and all patients had a normal remaining renal moiety confirmed on postoperative Doppler ultrasound. Mason et al. [25] reviewed another 21 patients with a mean age of 4.1 years, mean operative time of 301 min, blood loss of 36 mL, and length of stay 38 h. The authors primarily used three ports but for increased retraction purposes, a fourth robotic working port can be used and placed in a similar location to the assistant port on the other side of the camera. Twenty-nine percent of the cases demonstrated an asymptomatic postoperative fluid collection, all of which were managed conservatively. Of note, fluid collections were found 42% of the time when the renal defect was not closed, compared to 11% of the time when the defect was closed, illustrating the need for reconstruction and the important role the robot can play in management.

2.3. Ureteroureterostomy

Robotic ureteroureterostomy was first reported in an adolescent female with an obstructed left upper pole system and crossed fused renal ectopia. A 4-port approach with a single 12 mm umbilical camera port, two 5 mm triangulated working ports, and a 5 mm assistant port placed above the anterior superior iliac spine was used. The case took 485 min and documented resolution of obstruction via diuretic renography was noted at 12 weeks [26]. Additional small case series consisting of 1—5 patients suggest robotic surgery represents a feasible approach for repair of ureteral anomalies in pediatrics, with a high success rate and minimal complications. Multiple authors emphasized the better visibility, improved suturing, and reduced narcotic utilization, and short hospital stays associated with robotic ureteroureterostomy [27—30]. A review of the literature for pediatric robotic ureteroureterostomy is summarized in Table 2.

These encouraging findings would be replicated both in the infant population [31] as well as in a single kidney transplant patient, who underwent transplant to native ureterostomy [32], with the authors reporting resolution/significant improvement of hydronephrosis in both instances.

Most recently, a bi-institutional comparison of robotic assisted laparoscopic *vs*. open ureteroureterostomy for duplex systems was published showing similar operative times and estimated blood loss, along with similar complication rates with four patients in each group experiencing febrile urinary tract infections and one patient in the open group experiencing post-operative ureterovesical junction obstruction [33]. Robotic excision of ureteral polyps with repair has also been reported [34].

2.4. Ureteral reimplantation

Robotic assisted laparoscopic ureteroneocystostomy for vesicoureteral reflux disease is usually performed through a transperitoneal, extravesical approach, mimicking the Lich-Gregior procedure. The 10 or 12 mm camera port is placed in the umbilicus and the 8 mm working ports are placed lateral and one hand breadth away, with a 5 or 12 mm assistant port placed on the ipsilateral side to the pathology, superior and midway between the camera and working port. Table 3 reviews the outcomes of studies involving pediatric robotic ureteroneocystostomy. Bilateral cases may be associated with urinary retention due to injury of the pelvic nerve plexus; however, bilateral extravesical nerve sparing reimplantation has been reported with good outcomes and all patients voiding spontaneously postoperatively [35]. When compared to open intravesical reimplantation, there is slightly higher operative time and episodes of urinary retention but shorter length of stay and decreased narcotic requirements with the robotic extravesical approach, but with similar success rates [36]. Other studies have shown improved success rates with surgeon experience [37]. Robotic ureteral reimplantation has also been used in obstructive cases with low rates of persistent obstruction or ureteral kinking at follow-up [38].

The intravesical/transvesical approach was initially reported in 2005 by Peters and Woo [39] in six children with no open conversions and one postoperative urine leak, and with resolution of reflux in all but one patient (83%). Marchini et al. [40] retrospectively compared a case-matched study of patients undergoing robotic reimplantation, performed either in an extravesical or transvesical fashion to open reimplantation using either the extravesical or intravesical technique. The robot was associated with longer operative times in both comparisons. For the intravesical comparison, the robotic approach had decreased bladder spasms with shorter duration of urinary catheter and hospital stay compared to open. No major differences were found between the two extravesical groups, and both extravesical groups had shorter length of stay compared to the intravesical groups. All groups had similar complication rates and rates of persistent reflux postoperatively.

The increased failure rates and complication rates have not helped the penetrance of robotic utilization for ureteroneocystostomy when compared to the excellent results achieved with the open approach. However usage has increased from 0.3% from 2000 to 2012 up to 6.3% in 2016 [41] probably because of increased access to the robotic system. It is usually reserved for larger children. The largest multi-institution study with five surgeons comprising 61 patients (93 ureters) was reported by Grimsby et al. [42] in 2015, demonstrating markedly decreased success rate of 72% (44 of 61 patients) with 14 cases of persistent reflux, six complications with five requiring immediate reoperation, and nine patients requiring reoperation. No correlations between hospital, age, gender, or bilateral *vs*. unilateral factors were found among the failure rates. Dangle et al. [43] found a 5.9% complication rate in unilateral extravesical reimplantations, which increased in bilateral procedures to 30.6%.

Despite these outcomes, pain score and narcotic usage have been shown to be greatly improved with the robotic approach compared to open techniques [44]. Also, in regards to patient perception of surgical scars, it has been noted that patients preferred robotic over open surgical scars in all cases with scar size being an important component of preference [45].

2.5. Bladder diverticulectomy

Bladder diverticula can develop as consequences of bladder outlet obstruction (e.g., posterior urethral valves), neuropathic bladder dysfunction, and with congenital defects at the ureterovesical junction (i.e., Hutch diverticulum). Diverticulae that retain urine, cause incontinence and urinary tract infections should be removed. A robotic approach can be performed safely along with ureteroneocystostomy, if indicated. Port placement is similar to robotic extravesical reimplantation. Illumination of the diverticulum by placement of a cystoscope facilitates its dissection. A diverticulum positioned along the posterior bladder wall precludes the need to drop the bladder. The ease of intracorporeal suturing with the robot improves detrusorrhaphy outcomes, in which the bladder should be closed in two layers. Christman reported on 14 patients (mean age 7.9 years) in which the mean operative time was 132.7 min and length of stay 24.4 h. There were no complications, and all patients had normal voiding cystourethrograms at follow-up. In the six

Table 2 Review of robotic ureteroureterostomy in children.

Author	No. of patients	Mean age (year)	Operative indication	Operative ports	Mean operative time (min)	Hospital stay (days)	Complications	Mean follow-up (week)	Success rate (%)
Yee and Shanberg, 2006 [26]	1	16	Obstructed left upper pole system and fused renal ectopia	4 (12 mm umbilical, 2 × 5 mm operative, 5 mm assistant)	485	3	None	12	100
Gundeti et al., 2006 [28]	1	12	Retrocaval ureter	3 (12 mm umbilical, 2 × 5 mm operative)	240	Not listed	None	26	100
Passerotti et al., 2008 [29]	3	9.5	Ureteral valve (1), inflammation (1), ureteral stone with stricture (1)	3–4 (12 mm umbilical, 2 × 5–8 mm operative, ±5 mm assistant)	244	3.5	None	11.6	66
Smith et al., 2009 [27]	2	8	Retrocaval ureter (1) and vessel entrapped ureter (1)	3 (12 mm umbilical, 2 × 5 mm operative)	283.5	1.3	None	5	100
Leavitt et al., 2012 [30]	5	5.1	Upper pole duplicated ectopic ureter (5)	3 (12 mm umbilical, 2 × 5 mm operative)	225	1.2	Pyelonephritis (1)	40	100
Bansal et al., 2014 [31]	2	0.75 (both under 1 year)	Obstructed ectopic ureter (1), congenital mid-ureteral stricture (1)	3 (8.5 mm umbilical, 2 × 8 mm operative)	127.5	1	None	40	100
Bowen et al., 2014 [32]	1	14	Transplant to native ureter (1)	3 (8.5 mm umbilical, 2 × 8 mm operative)	411	Not listed	Urine leak (1)	78	100
Lee et al., 2015 [33]	25	6.1	Duplex systems (23), midureteral obstruction (2)	3 (8.5 mm umbilical, 2 × 5 mm or 8 mm operative)	186	1.6	Febrile UTI (4)	66	86 (9 stable)

UTI, urinary tract infection.

Table 3 Review of robotic ureteral reimplantation in children.

Author	No. of patients	Mean age (year)	Operative indication	Surgical approach	Operative ports	Mean operative time (min)	Hospital stay (day)	Complications	Mean follow-up (week)	Success rate (%)
Peters and Woo, 2005 [39]	6	10	Bilateral VUR	Intravesical cohen cross-trigonal	3 (12 mm bladder dome, 2 × 8 mm operative)	Not reported	Range given: 2–4	Urine leak (1)	Not given	83
Marchini et al., 2011 [40]	19	9.9	Unilateral (2)/ bilateral (17) VUR	Bilateral intravesical (Glenn-anderson or Cohen) and extravesical	Not reported	232.6	1.8	Pain score >2 (8), bladder spasms (2), urinary retention (1), bladder leak (4)	84.3	92
Smith et al., 2011 [36]	25	5.75	Unilateral (17)/ bilateral (8) VUR	Extravesical	3 (12 mm umbilicus, 2 × 5 mm or 8 mm operative)	185	1.375	Transient urinary retention (4)	69.5	100 unilateral, 94 bilateral
Akhavan et al., 2014 [37]	50	7.2	Unilateral (22)/ bilateral (28) VUR	Extravesical	Not reported	Not reported	2.0	Febrile UTI (5), ileus (2), ureteral obstruction (2), ureteral injury (1), perinephric fluid collection (1), transient urinary retention (1), contralateral *de novo* VUR (5)	40.8	92.3
Grimsby et al., 2015 [42]	61	6.7	Cortical defects (35), breakthrough UTI (13), persistent VUR (12), noncompliance (1)	Unilateral (29)/ bilateral (32) extravesical	3 (8.5 mm umbilicus, 2 × 8.5 mm operative)	Not reported	Not reported	Ureteral obstruction (3), urine leak (2), rehospitalization for nausea and vomiting (1)	50.9	72

UTI, urinary tract infection; VUR, vesicoureteral reflux.

patients who had diurnal enuresis preoperative, this resolved after surgery [46].

2.6. Urachal cyst excision

Urachal anomalies can present as an umbilico-urachal sinus, urachal cyst, vesico-urachal diverticulum, or a patent urachus and should be removed when it persists or becomes infected. Laparoscopic treatment of urachal cysts is well described; however, there are scant data for the robotic-assisted approach in children. The robotic approach offers a large cosmetic benefit over the open approach if the bladder is deemed to be involved, as the initial open periumbilical incision would need to be lengthened or extended inferiorly to remove the bladder cuff. The robotic port sites are placed higher on the abdomen, with the camera port in the subxyphoid position, and the working ports placed laterally below the ribs. The bladder is dropped to completely dissect the cyst from the bladder, and cystoscopy is performed to exclude bladder involvement and the need for partial cystectomy with bladder cuff repair. A series of 11 patients of which three were children, who underwent robotic assisted laparoscopic urachal cyst excision reported a median operative time of 85 min (90 min for the children) and a median length of stay of 1 day. They reported a single complication in an adult [47].

2.7. Mitrofanoff procedure

The first robotic assisted laparoscopic appendicovesicostomy (Mitrofanoff procedure) was reported by Pedraza et al. [48] in 2004 in a 7-year-old male with a history of posterior urethral valves. Utilizing a transperitoneal approach with four ports the overall operative time was 6 h with estimated blood loss of 10 mL, and without complication. At 10 month follow-up, he was performing clean intermittent catheterization (CIC) every 6 h with continence between CIC. Other series on patients undergoing appendicovesicostomy with various etiologies such as posterior urethral valves, myelomeningocele, prune-belly syndrome, and multiple sclerosis have shown mean operative times of 180—352 min, hospital stays of 3—5 days, no intraoperative complications, and successful performance of CIC postoperatively. One report of minor incontinence was successfully managed with injection of dextranomer/hyaluronic acid via the Mitrofanoff. One postoperative urinary leakage which required open repair which was reported [49,50]. Initial reports of the use of robotic assistance for revision of appendicovesicostomy has been reported in a series of three patients with minimal blood loss and restoration of continence at median follow-up of 5 months [51]. Table 4 summarizes case series involving pediatric robotic Mitrofanoff procedures.

When compared to the classic open approach, operative times are usually longer (267 min *vs.* 224 min) with comparable blood loss and decreased length of stay (5 days *vs.* 8 days) and narcotic usage [52]. Grimsby et al. [53] reported the largest case series to date in 2015 comparing 39 robotic appendicovesicostomies to 28 open appendicovesicostomies. There was no significant difference in complication rates (26%—29%), but found the robotic group included complications of greater severity; three patients experienced Clavien three complications, all bowel obstructions, requiring secondary surgery.

2.8. Malone antegrade continence enema

The appendicocecostomy, or Malone antegrade continence enema (MACE) for intractable constipation or fecal incontinence, is often simultaneously performed with a Monti procedure (continent catheterizable ileovesicostomy) or appendicovesicostomy. Thakre et al. [54] reported a robotic reconstruction using a divided appendix to create both a MACE and a Mitrofanoff channel in a 10-year-old girl using four robotic ports with two of these being used to create each stoma. Operative time was 200 min, blood loss 10 mL, and there were no complications during the procedure. She was started on clears on the first postoperative day, did not require narcotics after the first postoperative day, and was discharged home 5 days after surgery. At follow-up, the child is performing CIC every 6 h and the MACE washout is effective without stomal leakage of stool.

2.9. Bladder augmentation

Robotic assisted bladder augmentation has been successfully performed in children with neurogenic bladder dysfunction. Five ports are utilized, with the camera port at or slight above the umbilicus, with two working ports on the left lateral to the rectus muscle, parallel and inferior to the camera port. On the right side an inferior working port with a superior 12 mm assistant port for which a laparoscopic bowel stapler can be passed, however a robotic hand-sewn bowel anastomosis is also possible as described by Gundetti et al. [55]. Ileocystoplasty is usually performed with a concomitant catheterizable channel, and bilateral extravesical reimplantations with good postoperative results [56]. Wille et al. [57] reported on 11 cases of enterocystoplasty with appendicovesicostomy with a mean age of 10.4 years, length of stay 6 days, and no intraoperative complications. All patients were continent and catheterizing without difficulty at follow-up [57]. When deciding how to place the Mitrofanoff robotically, Famakinwa et al. [58] found that an anterior wall extravesical anastomosis was associated with a slightly lower stomal complication rate compared to a posterior wall intravesical anastomosis that can be allowed when opening the bladder for enterocystoplasty.

Murthy et al. [59] reviewed their experience of 15 robotic bladder augmentations with associated procedures to 13 open bladder augmentations. The robotic group had a longer median operative time (623 min *vs.* 287 min) and blood loss (100 mL *vs.* 50 mL) but shorter length of stay (6 days *vs.* 8 days). There were no significant differences in complications, narcotic use, feeding, and postoperative percentages in bladder capacity between the groups.

2.10. Bladder neck reconstruction

Few reports of pediatric robotic bladder neck procedures exist in the literature. Robotic bladder neck sling placement (using a cadaveric human dermal allograft) was performed on two female patients aged 9 and 10 years with spina bifida and continued incontinence despite maximal pharmacotherapy and intermittent catheterization; urodynamics revealed low pressure bladders with normal compliance. Posterior bladder neck dissection, followed by dropping the bladder and anterior bladder neck dissection and perforation of the endopelvic fascia bilaterally was used as the dissection for sling placement, which was then placed using the cinch technique. There were no complications, operative times of 170 and 208 min, mean blood loss of 20 mL, and they were discharged home on postoperative days 2 and 4. At follow-up, both patients were continent and performing catheterization, with closed bladder necks on cystography and stable upper tracts [60].

One of the first case series to illustrate the feasibility of robotic bladder neck reconstruction detailed three patients with sphincteric incompetence and persistent urinary incontinence who underwent Mitrofanoff, Leadbetter/Mitchell bladder neck reconstruction, and bladder neck fascial sling completed with a mean operative time of 375 min, length of stay 2 days, and all patients dry on CIC and anticholinergics postoperatively [61]. Additional experience by Gargollo [62] detailed 38 patients (mean age 10 years) who underwent robot-assisted Mitrofanoff along with Leadbetter/Mitchell bladder neck reconstruction and bladder neck sling, with one patient undergoing robotic Monti procedure secondary to prior appendectomy. Mean operative time was 348 min with times significantly decreased after the first 10 cases. Four cases required conversion to open. Eighty-two percent reported continence with catheterization at follow-up. Complications included four cases of *de novo* reflux (grades II and III) and two patients who developed bladder stones.

Table 4 Review of robotic appendicovesicostomy in children.

Author	No. of patients	Mean age (year)	Operative indication	Operative ports	Mean operative time (min)	Hospital stay (day)	Complications	Mean follow-up (week)	Success rate (%)
Pedraza et al., 2004 [48]	1	7	PUV and resultant valve bladder syndrome	4 (12 mm umbilical, 2 × 10 mm operative, 5 mm left mid-axillary inferior)	360	4	None	43.5	100
Storm et al., 2007 [49]	2	13	Myelomeningocele (1), prune-belly syndrome (1)	5 (12 mm umbilical, 12 mm assistant, 5 mm assistant, 2 × 8 mm operative)	301	3	None	No mean provided, range 1–8 months	100
Nguyen et al., 2009 [51]	10	11.9	PUV (5), spina bifida with neurogenic bladder (3), nonneurogenic neurogenic (Hinman) bladder (1), spinal cord injury (1)	4 (12 mm umbilical, 2 × 8 mm operative, 5 mm suture port)	323	5	Postoperative urinary leak (1), minor incontinence (2)	61.7	80.00
Wille et al., 2011 [57]	11 (5 with combined augmentation)	10.4	Nonneurogenic neurogenic bladder (1), neurogenic bladder: tethered cord (1), spina bifida (1), arnold-chiari (1), sacral agenesis (2), prune-belly syndrome (3), myelomeningocele (2)	4 (12 mm umbilical, 2 × 5–8 mm operative, 5 mm assistant, ±10–12 mm assistant)	347	6	False passage of appendicovesicostomy (1), wound infection (1)	20	100
Wille et al., 2012 [52]	3	9.7	Prune-belly syndrome (3)	5 (12 mm umbilical, 2 × 8 mm operative, 5 mm assistant, 10–12 mm secondary assistant port)	352	3	Wound infection (1)	63.9	100
Grimsby et al., 2015 [53]	55	9.1	Myelomeningocele (27), PUV (11), idiopathic neurogenic bladder (7), prune-belly syndrome (5), bladder exstrophy (5), spinal cord injury (4), female epispadias (3), imperforate anus (2), sacral agenesis (1), transverse myelitis (1), megacystitis (1).	4 (12 mm umbilical, 2 × 8 mm operative, 12 mm assistant port)	Not reported	Not reported	Wound infection (2), hospital readmit (3), febrile UTI (2), bowel obstruction (3)	105.2	67

PUV, posterior urethral valves; UTI, urinary tract infection.

2.11. Miscellaneous procedures

2.11.1. Posterior urethral diverticula

Alsowayan et al. [63] reported on robotic repair of symptomatic posterior urethral diverticula proximal and lateral to the verumontanum in 2- and 4-year-old boys. They placed a catheter into the diverticula and distended it with saline to aid in identification and a hitch stich placed in the diverticula to help with complete dissection. The ureteral edges were closed with 5-0 suture and catheters left in place. Postoperatively, the patients had good stream with no urinary retention or strictures seen on voiding cystourethrography.

2.11.2. Prostatic utricles

Robotic removal of large prostatic utricles have also been described. One report discussed a patient with perineal hypospadias and a 10 cm utricle which persisted after failed conventional laparoscopic removal year prior. After robotic dissection with the aid of a catheter within the utricle, a stapler was passed through the assistant port and the utricle removed, leaving a small stump on the urethra. Foley catheter was removed 1 week after surgery and voiding cystourethrography 1 year later showed no strictures or cystic remnants [64].

2.11.3. Seminal vesicle cyst

Robotic excision of a symptomatic, cystic seminal vesicle in a 16-year-old male with ipsilateral renal agenesis and absence of the vas deferens. There were no complications and he was discharged home on postoperative day one, with resolution of symptoms at follow-up [65].

2.11.4. Varicocelectomy

Robotic-assisted varicocelectomy has been described, either transperitoneal laparoscopic or subinguinal without ports (for the use of the robot’s magnification advantages). For the transperitoneal approach, the robotic-assistance to laparoscopy shows to be technically feasible with avoidance of complications, but costs remain higher than conventional laparoscopic varicocelectomy [66].

2.11.5. Pediatric gynecologic surgeries

Robotic sacrouteropexy for adolescent patients with a history of bladder exstrophy and pelvic organ prolapse has been performed successfully, without recurrence at 1 year follow-up [67]. Robotic surgery for adnexal pathology (ovarian cystectomy, oopherectomy, salpingo-oopherectomy) was shown to be safe and effective, with mean operative times of 117.5 min, and without any complications or conversions, in six children aged 2.4—15 years and weighing 12—55 kg [68]. There is one reported case of a robotic-assisted vaginoplasty with bowel interposition in a 9-year-old girl with vaginal atresia. Robotic operative time was 135 min, and there was no complications and with minimal blood loss. Follow-up at one year showed a good cosmetic result with healthy tissue and maintenance of continence [69].

2.12. Oncologic procedures

While robotic surgery is well integrated into cancer management of the pelvis and kidney in adult urology, its role in pediatric oncology is not well defined. The robot affords more precise tumor dissection with the obvious reconstructive advantages that come with certain resections that conventional laparoscopic surgery is unable to achieve.

Recent European studies investigated the roles of laparoscopic and nephron-sparing surgery for renal masses in children, usually following neoadjuvant chemotherapy, with promising results. Cost et al. [70] performed a robotic-assisted radical nephrectomy with regional lymphadenectomy after preoperative chemotherapy (vincristine and dactinomycin) for a 6 cm centrally located right Wilms tumor in a 14-year-old girl. Total operative times was 210 min using four robotic ports and a lateral Pfannenstiel incision for specimen removal. Cost et al. also reported a robotic-assisted partial nephrectomy for a 1.5 cm left lower pole renal mass found to be renal cell carcinoma in a 14-year-old girl, along with a full aortic and hilar lymph node dissection. A laparoscopic ultrasound was used to help plan the resection; the total operative time was 180 min with 26 min of warm ischemic time. Five ports were used and the specimen was small enough to be removed through the assistant port, pathology revealed total resection with negative margins, and discharged home on postoperative day 2 with an uneventful recovery [71].

Adrenal-sparing surgery can also be achieved robotically. Rogers et al. [72] performed a 5-port robotic-assisted partial adrenalectomy with resection of extra-adrenal pheochromocytoma in a 14-year-old boy with von Hippel-Lindau syndrome. Tumor sizes were 3 cm for the extra-adrenal pheochromocytoma and 0.9 cm for the adrenal pheochromocytoma, all with negative margins. Operative time was 180 min with an estimated blood loss of 150 mL; the patient was discharged on postoperative day 4, normotensive and after an uneventful recovery.

The debate continues in many urologic oncology circles regarding the appropriateness of minimally-invasive retroperitoneal lymph node dissection. For the robotic approach, the arms are positioned in the midline with assistant ports in the lower quadrants, and robotic redocking is required if a bilateral procedure are to be performed. The use of lateral table rotation and slight Trendelenburg position are helpful, as are placing hitch stitches through the anterior abdominal wall and the serosa of the small bowel to aid in retroperitoneal exposure after reflecting the colon. Pediatric robotic retroperitoneal lymphadenectomy has been reported by Cost et al. [73] in one case of a 15-year-old male undergoing a right ipsilateral, nerve-sparing retroperitoneal lymph node dissection for an embryonal paratesticular rhabdomyosarcoma. Operative time was 357 min with 5 mL of estimated blood loss, 14 lymph nodes were obtained, and the patient was discharged home on postoperative day 2 with an uneventful recovery. At 16-month follow-up, he was doing well and remains disease free with normal antegrade ejaculation. In another case, a 15-year-old male underwent bilateral dissection following chemotherapy for a testicular mixed germ cell malignancy. A left hilar mass revealing mature teratoma along with ten negative lymph nodes were obtained, operative time was 527 min with

100 mL of estimated blood loss, the patient recovered well and was discharged home on postoperative day 2. At 1-year follow-up he was without issues, with normal antegrade ejaculation, and disease free.

3. Conclusion

The transition of robotic-assisted laparoscopic surgery to the pediatric population comes with its own specific set of challenges. Proper patient selection and alterations to the surgical procedure can be employed to yield successful outcomes. While pyeloplasty is the most common and best described robotic procedure in pediatric urology, many other operations have been reported and are currently utilized at some centers. Future improvements in technology with production of pediatric-sized robotic instruments, along with increases in robotic-trained pediatric urologists and surgeon experience along each's learning curve, will help to further advance the field of robotic surgery in pediatric urology. This evolution will offer alternative management in treating pediatric patients, with improvement of care and patient quality of life. Further research and time are required before we will truly see the full potential of robotic surgery as a therapeutic option in our pediatric patients.

Conflicts of interest

The authors declare no conflict of interest.

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