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Review Article

Review of robot-assisted laparoscopic surgery in management of infant congenital urology: Advances and limitations in utilization and learning

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Abbreviations & Acronyms

CO = cardiac output
CVP = central venous pressure
ICP = intracranial pressure
LMA = laryngeal mask
MAP = mean arterial pressure
ONSD = optic nerve sheath diameter
RAL = robot-assisted laparoscopic
RAL-P = robot-assisted laparoscopic pyeloplasty
SV = stroke volume
SVR = systemic vascular resistance
UPJO = ureteropelvic junction obstruction

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Abstract: As robotic-assisted (RAL) surgery expanded to treat pediatric congenital disease, infant anatomy and physiology posed unique challenges that prompted adaptations to the technology and surgical technique, which are compiled and reviewed in this manuscript. From the beginning, collaboration with anesthesia is critical for a safe, efficient case including placement of an endotracheal tube rather than a laryngeal mask (LMA) and placement of a nasogastric tube and/or rectal tube to relieve distended stomach or bowel, respectively. Furthermore, end-tidal CO_2 ($EtCO_2$) is important for monitoring and predicting the effects of pneumoperitoneum on caridiovascular physiology, incranial pressure, and risk of acidosis and hypercarbia. Positioning can further exacerbate these effects and affect intra-abdominal working space. For infant robotic pyeloplasty and heminephrectomy, a "beanbag" is commonly used for stabilization in the lateral decubitus position. We advise against the use of a "baby bump" because it brings the bowels and vasculature more anterior than expected. Pnuemoperitoneum pressure of 8–10 mmHg during port placement maximizes safety, but thereafter, the pneumoperitoneum pressure can be minimized to 6–8 mmHg during the procedure without compromising the visual field. Port sites should be marked after insufflation, followed by the open Hasson technique for peritoneal access and port placement under direct vision with intussusception of the trocars to avoid vascular or bowel injury. Additional tips can be obtained through this manuscript, immersive fellowships, and mini-fellowships. Ulitmately, infant robotic surgery has the potential to benefit many children but is presently limited by the lack of pediatric-specific robotic technology and its associated costs.

Key words: congenital, infant, pneumoperitoneum, robot-assisted surgery, urology.

HISTORY OF RAL PEDIATRIC UROLOGY

When robot-assisted laparoscopic (RAL) surgery was introduced over two decades ago, the technology was adopted by pediatric urologists[1,2] for the management of congenital disease, including procedures such as pyeloplasty for treatment of ureteropelvic junction obstruction (UPJO)[3] and ureteral reimplant for management of vesicoureteral reflux (VUR) and obstruction. The new RAL technology offered features that were not available by traditional open approach or even by laparoscopy,[4] which was the predominant minimally invasive surgical approach at the time RAL was introduced.

Unlike laparoscopy, the RAL technology, specifically the da Vinci robotic surgical system (Intuitive Surgical), is equipped with high-resolution three-dimensional (3D) view, 10-fold magnification, tremor filtration with motion scaling, instrument movement that mimicked wrist-like motion, and camera positioning controlled by the surgeon.[2,5] Surgeons hoped these enhancements would improve intra-corporeal suturing, precision, and proper tissue handling, especially in complex surgical cases. Despite high interest in expanding successful application of RAL surgery, to our knowledge, no widely-ackowledged authorized guidelines exist for infant robotic surgery with consideration of anesthesia, technique modification, training and future developments.

BENEFITS OF RAL IN PEDIATRIC AND INFANT PATIENTS

Once implementation of RAL in pediatric urology surmounted the learning curve of skill acquisition, studies began to show comparable operative times, outcomes and complications to laparoscopic and open approach. In pediatric patients, studies examining robot-assisted laparoscopic pyeloplasty (RAL-P) demonstrated increased ease of instrument use compared to laparoscopic technique while delivering similar outcomes to gold standard open approach.[6–8] Presently, studies have shown that pediatric robotic surgery is associated with lower pain scores, less narcotic use, and shorter hospital stays.[9] Thus, so began the movement to implement RAL surgery in the infant patient population to offer them the benefits reaped by older pediatric patients, as aforementioned.[10–12]

The current literature on infant RAL pyeloplasty accounts for overwhelmingly positive outcomes, potentially due to a population of surgeons who adapted to pediatric RAL before infant RAL. Since the first successful infant RAL pyeloplasty, described in a series of nine patients with a mean age of 5.6 months,[11] subsequent single- and multi-center studies have been published, including our own large single-center institutional series.[5] Overarchingly, recent studies report similar success (typically defined as resolution or improvement of hydronephrosis by postoperative ultrasound) and complication rates, with shorter length of stay for RAL pyeloplasty than for open pyeloplasty.[12–16]

For instance, evidence supports robotic surgery in infants due to equivalent surgical outcomes with the benefit of improved cosmesis. Multiple incisions from small robotic ports may also be advantageous in tissue healing and postoperative pain.[17] When compared to one longer open surgery incision, studies have shown that smaller incisions have less collagen deposition and less total tension.[18] Risk of severe scarring, such as keloids, is greater in high-tension wounds.[19]

While the current literature describes the benefits of RAL surgery in infants, before such evidence, there was initial concern about feasibility and safety. More specifically, infant anatomy and physiology posed unique challenges that were not always inherently compatible with the RAL technology and the associated intra-abdominal working space requirements, both of which will be addressed in the following sections.

RAL INFANT PHYSIOLOGY AND ANESTHESIA

Children have unique physiologic and anatomic differences that should be considered pre-operatively and intra-operatively in minimally-invasive surgery. For example, it has been noted that pediatric patients have faster gastric emptying times which may lead to increased small bowel distention and subsequent compromise of access and visualization. Additionally, in pediatric patients, the bladder is shifted into the abdominal space, rather than deeper in the pelvis in adults. Furthermore, in children, increased abdominal wall laxity can create higher risk for vascular or bowel injury when gaining trocar access.[20] Collaboration with anesthesia is essential to mitigate these special considerations and will be discussed in the following subsections.

Anesthetic team

From the start of any infant RAL case, an anesthesia team with training or experience in pediatric laparoscopic surgery is critical to the safety and success of the case. Prior to intubation, infants may receive mask ventilation and subsequently present with dilated intestinal distension due to aerophagia, which can limit visibility intraoperatively if not intervened upon. Placement of an endotracheal tube rather than a laryngeal mask (LMA) and facemask can limit distension of the stomach and bowel. Furthermore, especially in left-sided cases, placement of a nasogastric tube can relieve distended stomach or bowel and increase the operative field. Because infants have relatively faster gastric emptying and increased bowel distention compared to older children, placement of an endorectal tube may also be helpful. Lastly, due to the shorter head-to-toe length of infant patients, there is increased congestion as the anesthesiologists, surgeons, and robot are in closely proximity to one another. Because of this, it is worth mentioning the importance of establishing two lines for intravenous access with one that is immediately accessible and unobscured by drapes and straps.

Pnuemoperitoneal pressure

In a prospective, randomized study, 46 infants (less than 10 kilograms in weight) who underwent RAL surgery were analyzed based on physiologic changes and pneumoperitoneal pressure (PP) (Group I, n = 23, PP = 6–8 mmHg and Group II, n = 23, PP = 9–10 mmHg).[21] Hemodynamic, respiratory, and blood gas changes were measured at four points: before CO_2 insufflation (T0), 10 min after insufflation (T1), before desufflation (T2) and 10 min after desufflation (T3).[21] Recorded outcomes included required adjustments of ventilator parameters, postoperative pain, analgesic use and time to resume feedings at 1, 6 and 12 h postoperatively. Technical feasibility with allocated PP was evaluated by means of successful completion of surgery, duration of surgery, and intraoperative complications.

At T1 and T2, changes in hemodynamic and respiratory parameters were significantly higher in Group II. At T3, most of the parameters statistically restored back to baseline in Group I but not in Group II. Number of required adjustments in ventilatory parameters were 14 vs. 25 events in Group I vs. Group II (p = 0.007, R = 0.552).[21] Mean postoperative pain score, requirement for analgesia, and time to resume feeding were significantly greater in Group II.[21] Surgeries were successfully completed in all the patients in both groups, with comparable duration of surgery and similar intraoperative complications. This study comparing outcomes of variations in PP during RAL surgery in infants highlights their unique physiology and the necessary subsequent adjustments.

Safe insufflation and end tidal CO_2

It is well known that carbon dioxide (CO_2) insufflation, used during laparoscopic and RAL surgery, can lead to hypercapnia and acidosis by carbon dioxide absorption. Surrogate markers for carbon dioxide absorption include arterial partial pressure of CO_2 ($PaCO_2$), end tidal CO_2 ($EtCO_2$) and pH and are correlated with acidosis and hypercapnia.

In a study of 30 patients, including neonates, who underwent minimally invasive surgery for congenital diaphragmatic hernia (CDH), one study found that a decrease in insufflation pressure in CDH repair cases was associated with a significant decrease ($p = 0.002$) in peak $PaCO_2$ and an improvement in nadir pH ($p = 0.01$) in patients.[22] This study reinforces the relationship between carbon dioxide insufflation, risk of acidosis and hypercarbia, and measurements for monitoring carbon dioxide levels, specifically end tidal carbon dioxide ($EtCO_2$).[22]

In another study, at a single institution, changes in end-tidal carbon dioxide ($EtCO_2$) were analyzed intra- and post-operatively among 84 infant cases, with a median operative age of 2.2 months and median operative body weight of 4.2 kg, who underwent various laparoscopic procedures, with a median operative time of 3.5 h and median insufflation time of 2.0 h. They concluded that the intraoperative $EtCO_2$ level was significantly higher for longer operative time ($p = 0.01$) and insufflation time ($p < 0.001$). However, $EtCO_2$ returned to normal when CO_2 insufflation was stopped.[23]

In one retrospective analysis of 50 infant pyloromyotomy cases (22 laparoscopic, 28 open), there were no significant differences in operative time, temperature change, heart rate, and blood pressure.[24] As anticipated, in laparoscopic procedures, with insufflation pressures of 8–10 mmHg, there was a statistically significant increase in end-tidal CO_2, although none of the end-tidal CO_2 values rose above 6 kPa, a value that defines hypercapnia. It is concluded that laparoscopic pyloromyotomies undertaken in small infants with insufflation pressures of 8–10 mmHg are without significant adverse physiological effects when operative time is not prolonged compared to open procedures. These findings support the conclusion that laparoscopic surgery for neonates and infants can be safely performed by experienced surgeons and anesthetic teams.

Pneumoperitoneal pressure on intracranial pressure

During laparoscopic procedures, physiologic changes are caused by (1) increased intra-abdominal pressure by pneumoperitoneum, (2) gas absorption into the bloodstream, and (3) patient positioning, specifically, Trendelenburg or reverse/anti-Trendelenburg.[25] Studies have shown strict relationship between increase in intra-abdominal pressure, positioning, and CO_2 absorption to increase in mean arterial pressure (MAP), systemic vascular resistance (SVR), and central venous pressure (CVP) with a decrease in cardiac output (CO) and stroke volume (SV).[26] Pneumoperitoneum has both neuroendocrine and mechanical effects on cardiovascular physiology.[27] Increased intra-abdominal pressure may cause catecholamine release and subsequent activation of the renin aldosterone angiotensin system (RAAS), causing increased mean arterial pressure (MAP) and systemic vascular resistance (SVR).[27] Mechanical effects depend on the patient's pre-operative volume status (anemia, hypovolemia) and intra-abdominal pressure, which can cause compression of arterial and venous vasculature and increase SVR. Patients with normal cardiovascular function can tolerate variations in preload and afterload well but, special considerations should be acknowledged for infants.

For instance, if the intra-abdominal pressure raises above 15 mmHg due to excessive gas pressure insufflation or because of abdominal wall muscle contraction (coughing, abdominal wall resistance due to insufficient muscle relaxant) the vena cava can be compressed, causing decreased venous return and cardiac output.[25] In newborns and infants under 6 months old, the risk of low cardiac output at 15 mmg Hg of intra-abdominal pressure is higher due to low contractility and compliance of the left ventricle. Additionally, there is risk, albeit relatively low, of reopening right–left shunts, which can result in cardiac insufficiency and systemic gas embolism.

Lastly, careful consideration should be given to the effects of pnuemonperitoneum and positioning on intracranial pressure in this special population. Meta-analysis of 9 observational studies and one randomized controlled trial, with a total of 460 subjects, revealed that elevation in intracranial pressure (ICP) during laparoscopy could be anticipated through a significant increase in the optic nerve sheath diameter (ONSD) in the early (0–30 min) and late (30–120 min) periods during CO_2 pneumoperitoneum.[28] Another study investigated intracranial pressure resulting from carbon dioxide pneumoperitoneum by measuring ONSD by ultrasound in 25 children (mean age 4.4 ± 1.9 years) undergoing laparoscopic surgery.[29] They found that during CO_2 pneumoperitoneum, ONSD increased significantly compared with ONSD after anesthesia induction (T0: 4.3 ± 0.3 mm, T1: 4.6 ± 0.3 mm, $p < 0.05$). In all patients, no neurologic complications were observed during the intra-operative or post-operative period. Given the available evidence, one may conclude that increases in intracranial pressure are related to pneumoperitoneum. However, until the short- and long-term consequences are better understood, this information should inform pre-surgical planning and efficiency, where applicable. For instance, risk can be mitigated through intentional positioning and safe insufflation pressure. Special caution should be used in procedures with longer anticipated operative times and the use of Trendelenberg and reverse/anti-Trendelenberg positioning. Patient positioning to maximize both safety and the visual field are discused in-depth in the following section.

SOLUTIONS TO OPTIMIZE INTRA-ABDOMINAL WORKING SPACE

Identifying limitations

In 2008, RAL technology was trialed in models designed to mimic infant intra-abdominal space and it was concluded that surgeon performance was limited by the restricted degree of motion.[30] It is well-known that one study found an inverse relationship between patient anterior superior iliac spine distance, puboxiphoid distance and the number of instrument collisions.[31] However, it was later countered that space limitations could be overcome using simple tricks, such as patient positioning, port triangulation, and manipulation of the robot arms. Because infants have a relatively shorter and wider abdominal wall surface area, moderate abdominal wall thickness, and relatively distended bowel compared with older children,[32] surgeons have adapted patient positioning, port placement and instrument selection to prioritize safety and maximize working space. The previously-mentioned studies detailing the physiologic sequela of excessive pneumoperitoneal pressure in infants has prompted surgeons to consider how to safely increase intra-abdominal working space in infants without compromising increased risk of hypercapnia and acidosis.

Infant positioning

With regard to patient positioning, the literature gives special attention to utilizing the "beanbag" for stabilization in the lateral decubitus position, with the use of an small axillary roll to prevent injury.[20,33] We advise against the use of "baby bump" (rolled up egg crate cushions) to position smaller patients for access to the flank, because this brings the bowels and major vasculature more anterior than expected. For infant pyeloplasty, we have previously published salient tips for successful infant pyeloplasty including positioning the contralateral ("down") arm in a flexed positioning with adequate padding; the ipsilateral arm ("up") is recommended to be secured to the infant's side.[34] We do not flex the table because of the flexible nature of the neonate spine and a flexed table may cause vessels to be more superior and/or anterior, which can be hazardous for port placement. Rather than 90 degrees perpendicular to the surgical table, the patient is positioned in a 30-degree tilt from the lateral plane to push away the bowels.[35] The infant is secured to the table with folded blue towels and silk tape at the rib cage and hips, with caution at the rib cage to avoid excessive tightness of the straps.

Insufflation and port placement

Infant and pediatric RAL surgeons and anesthesiologists have developed age-dependent guidelines for insufflation pressures, which are as follows: 0–2 years, 8–10 mmHg; 2–10 years, 10–12 mmHg; 10–18 years, 12–15 mmHg.[20] We have found that pnuemoperitoneum pressure of 8–10 mmHg during port placement maximizes safety but thereafter, the pneumoperitoneum pressure can be minimized to 6–8 mmHg during the procedure without compromising the visual field.

To adjust for increased abdominal wall girth with pneumoperitoneum, surgeons may mark robotic ports after insufflation.[20] We recommend consistent practice of always placing ports under vision with manual control of the camera, preferably a zero-degree lens, which can be used for the duration of the case in instance of infant pyeloplasty. The use of an 10-mm balloon trocar with a 8-mm robotic canula can be set up to allow the robot camera to go through the apparatus and be docked. The camera facilitates the application of an outward traction, allowing for a wider range of motion of the scope and safer trocar setup. Open Hasson technique for peritoneal access and intussusception of the trocars (port in port technique) during placement are recommended to avoid vascular or bowel injury.

After insufflation, the thin abdominal wall may be insufficient to prevent trocar dislodgement or to maintain the working ports in an upward and outward position. To overcome this, Gundeti et al has suggested marking a circle with an 8-mm canula, adminsistering local anesthesia, and then incising the skin across the circle to grant tight fitting of the trocars.[33] Other experienced surgeons suggest anchoring the trocars to the skin with stitches to prevent dislodgement.[20] However, this will add to the surgical time and limit the surgeon's ability to adjust the port length if needed. Finally, the use of the AirSeal® device is advantageous in keeping pneumoperitoneum when an assistant port is needed.

To reduce arm collision with the da Vinci Si, X, or Xi platforms, it has been suggested to move the robot arms in a more linear and less triangulated fashion and place the working ports on the midline. For infant pyeloplasty, we suggest placement of all ports in the midline with 3–4 cm between each port, as the area of interest is within a confined region (eg. renal pelvis, ureteropelvic junction). One to two centimeters of additional space for safe maneuvering can be gained by the method of "burping" the robotic arms.[33] The previous seven sub-sections are summarized in Table 1.

Limitations and adaptation of surgical instruments

As the robotic platform and its technology have been adapted to fit the needs of infant anatomy and pathology, there have been inconsistent reviews on the utility of 5-mm instruments in infant RAL surgery. In 2018, 65 pediatric (16 infant, 49 non-infant) RAL pyeloplasty cases were performed using an 8.5-mm camera and 5-mm robotic instruments and found that the use of 5-mm instruments in infant cases did not affect outcomes but did offer potential for improved cosmesis.[36] On the contrary, Boysen et al points out that although 5-mm robotic instruments are available for pediatric use, these instruments have a pulley system that limits instrument articulation, especially in confined spaces like the pelvis, and thus recommends the use of 8-mm instruments for pediatric cases.[34] Andolfi et al describes how differences between the 8- and 5-mm instruments can be critical in the infant intra-abdominal working space.[33] The "smaller sized" 5-mm instruments are a misnomer as they have a longer wrist distance and require an additional 2-cm working distance within the abdomen compared to the articulated wrist joint of the 8-mm instruments. Further, the longer distance between the tip and the joint of the 5-mm instruments dramatically decreases the degrees of freedom and range of motion, especially while performing in small surgical fields, such as infant patients. The vertebral joints of the 5 mm instrument wrists have a greater radius of curvature and therefore require more space to make them angulated than cardan-jointed 8 mm instruments (Figure 1).

In the da Vinci Si and S systems, there is a limited selection of 5-mm instruments including lack of bipolar energy source in the 5-mm dissectors. Surgeons have adapted to this by utilizing the monopolar hook for cautery during dissection. Additonally, 5-mm curved scissors with cautery are not available and thus, only "cold" cutting is available. While cases such as pyeloplasty can be adapted for dissection with a 5 mm DeBakey

TABLE 1 Summary of salient tips for infant RAL

Pneumoperitoneal pressure

- Utilization of end-tidal CO_2 ($EtCO_2$) to monitor and mitigate risk of acidosis and hypercarbia
- Intra-abdominal pressure (>15 mmHg), positioning, CO_2 absorption effects:
  - Increase mean arterial pressure (MAP), systemic vascular resistance (SVR), central venous pressure (CVP), intracranial pressure (ICP)
  - Decrease in cardiac output (CO), stroke volume (SV)

Positioning

- Pediatric "beanbag" in the lateral decubitus position
- 30-degree tilt from the lateral plane, rather than exactly perpendicular
- Axillary roll to prevent injury
- Omission of "baby bump" under the flank
- Patient secured at hips and rib cage

Anesthesia, insufflation, and port placement

- Placement of orogastric (OG) or nasogastric (NG) tube and/or rectal tube for stomach or bowel decompression, respectively
- Guidelines for insufflation by age: 0–2 years, 8–10 mmHg; 2–10 years, 10–12 mmHg; 10–18 years, 12–15 mmHg
- For infants: 8–10 mmHg for port placement, 6–8 mmHg for procedure
- Mark ports after insufflation: with 8-mm canula, mark a circle then incise across the circle for tight-fitting trocars
- Place ports under vision with manual control of zero-degree lens
- 10-mm balloon trocar with a 8-mm robotic canula to dock camera
- "Burping" of robotic arms
- Use of 8-mm instruments due to limitations of 5-mm instruments

grasper and a 5 mm monopolar hook,[36] other infant RAL cases with more vasculature involved may require 8 mm cautery instruments or 5 mm cautery instruments that are not yet available. We acknowledge the need for pediatric-specific robotic instruments and support manufacturing and modification of smaller tools, such as a 5-mm balloon trocar and a scope with 3-mm working ports and instruments. Innovations in robotic instruments would improve surgical capabilities, surgeon ergonomics, and decrease the risk of incisional hernia.

Applications

Infant robot-assisted laparoscopic pyeloplasty (IRAL-P)

While the majority of infant RAL have been pyeloplasty cases, given the population and pathology of ureteropelvic junction (UPJ) obstruction, RAL technology continues to progress in the infant population. Application of infant RAL has expanded to include treatment of other renal pathology by heminephrectomy, ureteroureterostomy, and pyeloplasty in duplex collecting systems.[37,38] As such, we feel it useful to briefly provide salient tips and outcomes for said procedures from our own experience and success. With regards to infant pyeloplasty, the greater majority of this review should prove to be helpful but, a few additional comments include the use of a zero-degree lens for port placement and the duration of the procedure. To reduce operative time and subsequently limit anesthetic exposure and duration of carbon dioxide pneumoperitoneum, we selectively perform cystoscopy and retrograde pyelogram in specific cases including redo pyeloplasty and anomalous anatomy. Instead of a double-J (JJ) stent which crosses both the ureteropelvic junction (UPJ) and ureterovesicular junction (UVJ), we opt for a cutaneous pyeloureteral stent (CPU),[39] which we fashion from a JJ stent by removing the distal coil and placing the stent percutaneously. The stent transverses the renal pelvis, without puncturing renal parenchyma, thus limiting puncture bleeding and improving blood loss, hemostasis, and the visual field for completion of the anastomosis. In our experience, 6–0 PDS is preferred for ureteral reconstruction and risk of hernia is minimized by diligently closing ports under vision. A summary of our salient tips for infant robotic pyeloplasty are shared in Table 2. We have shared previously shared our outcomes of 44 infants, defined as less than 1 year old at the time of surgery, who underwent RAL pyeloplasty for ureteropelvic junction obstruction between January 2012 and August 2019.[33] All robotic cases were completed successfully, with no intraoperative conversions to open. The median age and weight were 4.0 months (1.0–12.0 months) and 6.8 (3.8–10.5) kg, respectively. The mean operative time was 142 (±25) min. The mean length of hospital stay (LOS) was 1.4 (±0.7) days. Seven (15.6%) patients had postoperative complications—one (2%) ileus (Clavien-Dindo grade [CDG] I), four (9%) urinary tract infections (CDG II), and two (4.5%) port-site hernias (CDG III). At a median follow-up of 19 months, the success rate was 100%. Our updated infant RAL pyeloplasty outcomes through December of 2021 are shared for the first time in Table 3.

Infant robot-assisted laparoscopic heminephrectomy (IRAL-HN)

Regarding salient tips for success in robot-assited laparoscopic heminephrectomy, we have previously published single-institution and multi-institution data for heminephrectomy and ureterectomy.[37,38] Indications for heminephrectomy

FIGURE 1 Da Vinci S/SI 5-mm instrument with vertebral wrist (Left); Da Vinci S/SI 8-mm instrument with articulated cardan-joint wrist (Right).

TABLE 2 Infant robotic (RAL) Pyeloplasty (IRAL-P): Salient tips for technique

1. Selective cystoscopy and retrograde pyelogram in redo cases and anomalous anatomy
2. Position with "beanbag" in lateral decubitus with 30-degree tilt from the lateral plane
3. Pneumoperitoneum: 8–10 mmHg for port placement, 6–8 mmHg for procedure
4. Port sites marked after insufflation, along midline with 3–4 cm between each port
5. Ports placed under direct vision with zero-degreee lens
6. Cutaneous Pyeloureteral (CPU)[a] stent to minimize puncture bleeding and anesthesia exposure
7. 6–0 PDS for ureteral reconstruction
8. Port closure under vision to reduce hernia risk

[a]Dangle, Pankaj P et al. "Cutaneous pyeloureteral stent for laparoscopic (robot)-assisted pyeloplasty." *Journal of endourology* vol. 28,10 (2014): 1168–71. doi:10.1089/end.2013.0499.

TABLE 3 Outcomes of infant robotic (RAL) Pyeloplasty Single Surgeon, October 2010 to December 2021

N	50
Op Time Mean (SE) in minutes	140.0 (25.7)
Length of stay Mean (SE) in days	1.3 (0.5)
Clavien Dindo	
Clavien Dindo I *n* (%)	1 (2)
Clavien Dindo II *n* (%)[a]	6 (12)
Clavien Dindo III *n* (%)	7 (14)
CD-III: Hernia	3
CD-III: Stent placement or replacement	2
CD-III: Redo pyeloplasty or Ureterocalicostomy	2
Success rate *n* (%)	48 (96)
Follow up Mean (SE) in months	16.6 (13.8)

[a]Urinary tract infection and/or port-site infection requiring post-operative antibiotics.

in infants and children includes non-functioning upper or lower pole in duplex collecting systems, recurrent urinary tract infection, and/or associated vesicoureteral reflux.[37] Successful heminephrectomy outcomes include stabilization in kidney function and/or resolution of symptoms. In brief, our technique for infant RAL heminephrectomy varies from that of our pediatric heminephrectomy technique by a few key steps (Table 4). Cystoscopy, retrogram pyelogram, and ureteral catheter placement are all omitted, as the anatomy can be easily identified with excellent vision and dissection. Use of 8-mm ports and instruments are used for both pediatric and infant (less than 1 year) patients due to the limitations of 5-mm instruments. Figure 2 illustrates positioning for renal cases (pyeloplasty, nephrectomy) in children greater than 1 year old. Modification for infant patients includes working ports located along the midline. Our technique begins by exposing the affected kidney by reflecting the colon and incising Gerota's fascia. For example, after confirmation of the normal/lower moiety ureter, the diseased moiety ureter is

TABLE 4 Infant robotic (RAL) Heminephrectomy. Tips for retrograde technique

1. Omission of cystoscopy and retrograde pyelogram
2. After confirmation of normal moiety ureter, diseased moiety ureter is transected
3. Transect vasculature of the diseased moiety with harmonic scalpel; clips are not desirable as space is constrained and clips may come off
4. Transect the diseased moiety by entering the pelvicalyceal system of that moiety so the remaining moiety pelvicalyceal system is intact
5. Cut margin left open
6. Diseased ureter mobilized by blunt dissection to the common sheath, transected
7. For refluxing pathology, close stump with 4–0 polydioxanone suture

transected and passed posteriorly to the renal hilum cranially (a retrograde technique as described by Malik et al 2015), which helps identify vasculature of the upper moiety to be transected with harmonic scalpel, as the placement of clips is difficult in this small space.[37,38] Interestingly, there has been recent mention of firefly technology for identification of the vessels to be resected, which could be helpful but may or may not be inherently compatible for use in pediatric and infant populations and may require adaptation for use. With regard to the remainder of the procedure, the cut margin is left open. The distal stump of the diseased ureter is then mobilized by blunt dissection to the common sheath, where it is transected and then closed with 4–0 polydioxanone suture if the ureter pathology was refluxing in nature. For ureterocele pathology, the stump is left open. Our outcomes of infant RAL heminephrectomy are shared in Table 5.

TRAINING

As more studies demonstrate the benefits of RAL surgery in pediatric and infant populations, there is a drive to acquire RAL surgical skills. Recently, studies have started to investigate and quantify the "learning curve" of RAL surgery with a focus on number of cases needed to reach proficiency and the safety and outcomes while a surgeon climbs the learning curve. One study evaluated the first consecutive 33 pediatric robotic pyeloplasty cases performed by senior faculty at the initiation of their robotic surgery program and found that robotic operative time decreased with increasing experience.[40] After 15–20 robotic cases, operative time was within 1 standard deviation of operative time of open cases. Importantly, while summitting the learning curve, compared to open surgery, there were no significant differences in length of stay, pain scores, and success rates; most complications occurred at the beginning of the learning curve but with similar complication rates as compared to open procedures.[40]

Similar studies have examined RAL learning curve in infant patients.[41,42] While most studies demonstrate similar success and complication rates to open surgery once proficiency is achieved, the number of cases needed to reach proficiency, evidenced by improvement to plateau in operative time, is less agreed upon. In their initial experience with infant RAL pyeloplasty, Dangle et al found that operative

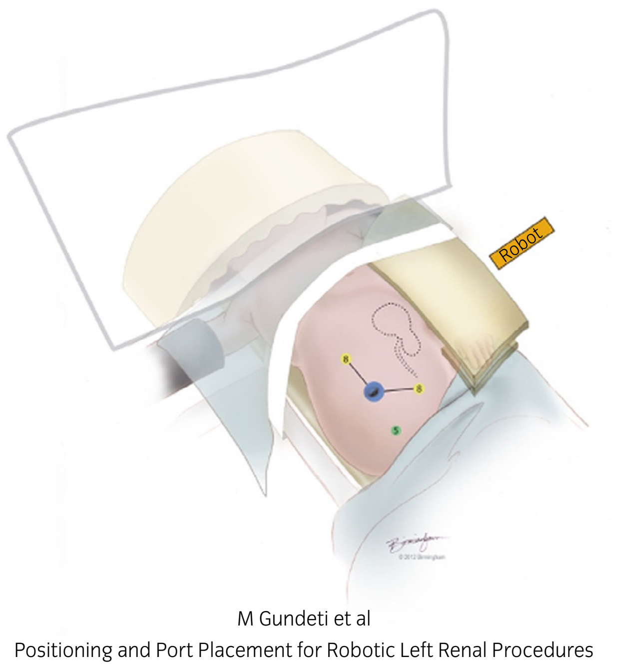

FIGURE 2 Renal procedure port placement for non-infant cases.

TABLE 5 Demographics and outcomes of infant heminephrectomy & nephroureterectomy: Single surgeon, September 2009 to December 2021

N	16
Age Mean (SE) in months	7.1 (2.6)
Weight Mean (SE) in kilograms	7.6 (2.1)
Op Time Mean (SE) in minutes	123.2 (23.5)
Length of stay Mean (SE) in days	2.0 (0.9)
Clavien Dindo III *n* (%)[a]	1 (6)
Success rate *n* (%)	16 (100)
Follow up Mean (SE) in months	21.4 (19.7)

[a]Hemorrhage into cavity requiring IR drain.

times decreased by 20 min after their first 5 robotic cases.[10] In a multi-institutional analysis of surgeons with prior non-infant RAL experience, we found that operative time decreased to a plateau after 13 RAL infant pyeloplasty cases.[5] Undoubtedly, surgeon experience and severity of disease pathology will influence any given surgeon's RAL learning curve in infant cases.

Acquisition of pediatric and infant robotic skills still remains the responsibility of the surgeon. Options for formal skill acquistion include robotic surgery fellowships and mini-fellowships, which rely on the role of an experienced mentor to guide the trainee in real-time and may or may not focus on the infant population. If a mentor is not available at a given institution, a mini-fellowship at another institution can offer experienced open surgeons with a brief but immersive introduction to robotic surgery. The mini-fellowship offered at our institution typically consists of didactic, observed RAL surgery, robot simulation, or porcine model. Given their unique anatomic and physiologic parameters, infants are a special patient population. We suggest that to best surmount the infant RAL learning curve, a surgeon should first be comfortable with pediatric RAL cases before embarking on infant RAL cases. Specifically, for success in infant pyeloplasty, we have previously recommended that the senior surgeon have experience of at least 25–50 toddler or teenage cases.

RAL FUTURE DIRECTIONS

As RAL technology expands in its applications, surgeons have identified its limitations but also adapted. While the aforementioned tricks are innovative and useful, we believe that pediatric and infant RAL remains limited by the lack of pediatric-specific robot technology. Future efforts to improve the functional design of 5-mm instruments or to engineer 3-mm instruments are needed to advance the field and keep pace with the speed at which RAL surgery has expanded in its applications. Of note, the newer Da Vinci Xi model has been well-received for its increased flexibility in camera and arm positioning, which can be helpful in the smaller infant intra-abdominal working space. Resources aside, the most effective innovation may be newer robotic platforms specifically designed for use in pediatric populations. For instance, we believe that pediatric surgery would benefit from engineering a 5-mm camera and robot arms that are more flexible for easier docking. Alternatively, within pediatrics, there would be use for robot arms that could be mounted on a table rather than the larger floor system.

We must exert pressure to create a system designed for pediatric cases, to put the children first and perform more intra-abdominal surgery without limitations, especially in an industry that leverages technology for profit rather than considering its impact on health and humanity, especially in children. Without a change in demand put on existing manufacturers or increased supply by new competitors, innovation cannot accelerate to its maximum potential. Furthermore, the limited market has resulted in a monopoly that inflates the cost of the platform, maintenance and disposable instruments. On a larger scale, outside of the current advances and limitations of RAL technology in infant urology, adoption of RAL is constrained by initial investment costs and the lack of available options in robot systems. To move forward and make RAL technology more widely available for the benefit of children, more affordable robot models would grant access to more surgeons and patients. Alternatively, institution-specific financial modeling find that the initial investment costs are justified to meet patient demand, improve cosmesis and healing, and yield shorter hospital length of stay. Adoption of robotic technology is an essential component of digital surgery and advancements in care including upcoming 3D printing, augmented reality, and machine learning applications for training and assessment.

This manuscript aims to offer a collection of various perspectives and expertise for optimization of RAL technology for the benefit of the infant patient population. In doing so, presented information may compound to yield a clearer solution and in other instances, varying experiences may point out the work that is yet to be done. In either case, it is our belief that shared knowledge is valuable for the betterment of patient care, with specific aims to aid in safe, widespread adoption of RAL technology for surgical correction of pathology in infant urologic patients.

AUTHOR CONTRIBUTIONS

Alyssa M. Lombardo: Writing - original draft; Writing - review & editing; Formal analysis. **Mohan S. Gundeti**: Conceptualization; Writing - review & editing; Supervision.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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