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ADVANCES IN MINIMALLY INVASIVE SURGERY FOR THE MANAGEMENT OF UPPER URINARY TRACT ANOMALIES IN CHILDREN

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ABSTRACT

Background. Minimally invasive surgery (MIS) has significantly evolved in pediatric urology, offering alternatives to traditional open techniques by reducing postoperative morbidity, improving cosmetic outcomes, and accelerating recovery. Technological advancements, especially the miniaturization of instruments and the introduction of robotic systems, have expanded the indications and efficacy of MIS for upper urinary tract anomalies in children.
Aim. To review the current applications, outcomes, and future directions of minimally invasive techniques in the treatment of upper urinary tract anomalies in the pediatric population.
Material and Methods. This narrative review summarizes data from published literature regarding laparoscopic and robot-assisted procedures in pediatric urology. It analyzes indications, technical considerations, benefits, limitations, and comparative outcomes of MIS versus open surgery, focusing on procedures such as pyeloplasty, nephrectomy, ureteroureterostomy, and ureterocalicostomy.
Results. MIS approaches demonstrated reduced hospital stays, less blood loss, lower opioid use, and improved cosmetic results with comparable complication rates to open surgery. Robot-assisted procedures, particularly pyeloplasty, showed promising safety and efficacy—even in infants—and allowed for outpatient, stent-free interventions. Challenges remain in cost, equipment scaling for pediatric patients, and training requirements.
Conclusions. MIS, including robotic-assisted surgery, is becoming the gold standard for many upper urinary tract interventions in children. Continued technological advancement and surgical expertise are expected to further enhance outcomes, expand indications, and improve the quality of care in pediatric urology.

KEYWORDS

Minimally Invasive Surgery, Pediatric Urology, Robotic-Assisted Surgery, Laparoscopy, Urinary Tract, Pyeloplasty, Nephrectomy, Ureteroureterostomy, Ureterocalicostomy

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1. Introduction

Minimally Invasive Surgery (MIS) is an area that is still in a phase of dynamic development. There are many new tools and techniques that can improve treatment outcomes, reducing the risk of complications and shortening recovery time [1]. Although minimally invasive techniques like laparoscopy are well-accepted in adult surgery, their application in pediatric surgery is more complex. Technological progress, including the miniaturization of instruments adapted to the body structure of infants and small children, has enabled the rapid development of MIS in pediatric urological procedures [2]. Discussions among pediatric surgeons and urologists about laparoscopy no longer concern whether it is feasible, but rather how it can best be effectively used and adapted to various conditions. Over 90% of operations that previously required large incisions can now be safely performed using minimally invasive techniques [3]. Researchers point out a number of advantages resulting from the use of MIS. Significant benefits come from equipment that perfectly illuminates and magnifies the image of anatomical structures, which significantly improves visibility, especially in infants and smaller children. Furthermore, a panoramic view of the abdominal and pelvic cavities allows for simultaneous operations on the upper and lower urinary tracts within a single procedure, which previously required several stages and different incisions [4]. What's more, in young children and infants, limiting postoperative pain and stress is crucial. MIS minimizes tissue trauma, which translates into less pain, shorter hospital stays, and faster recovery. Additionally, small incisions with laparoscopy leave minimal scars, resulting in a better cosmetic outcome [5,6].

The next milestone in the development of minimally invasive surgery was robot-assisted laparoscopy. The main advantage of this system is that it offers less experienced surgeons the benefits of high robotic

dexterity [7]. The disadvantage of this system is the lack of tactile feedback. Therefore, visualization of anatomical landmarks is key to successful operation. The main surgeon is away from the table and must rely on an experienced assistant. Active communication between the main surgeon, first assistant, and staff is necessary. Although the learning curve for the surgeon may be short, there is a significant learning curve for supporting staff [8]. In view of the above, it should be remembered that laparoscopic surgery and other MIS urological procedures in children involve specific technical considerations and carry their own morbidity and complications. Each surgical approach requires different equipment, operating room setup, and technical issues that must be considered by the pediatric urologist. The aim of this review was to present current achievements in minimally invasive methods in pediatric urology, analyze current trends, and indicate possible directions for development.

2. Evolution of Minimally Invasive Surgery in Pediatric Urology

Initially, laparoscopy was not a widely accepted method in the pediatric population. This was likely due to the large amount of new instrumentation. The difficulty also lay in training personnel for the new method when classical operations were already well mastered. Additionally, the initial results of minimally invasive procedures depended on the experience of the surgical team, which was limited compared to the proficiency in open methods. The financial aspect remains a limiting factor in the development of laparoscopy in pediatric urology. As a very niche specialization, it was not an attractive field for investments by profit-oriented companies [9].

The first applications of urological laparoscopy began with a diagnostic procedure for the localization of the impalpable undescended testis, which significantly reduced unnecessary abdominal exploration [10]. The method evolved into therapeutic ranges thanks to research by Lindgren et al., who provided data on the effectiveness of laparoscopic orchiopexy [11]. Preliminary studies were confirmed by data from many centers, proving the effectiveness of this method and even its superiority over the traditional approach [12].

In subsequent years, researchers undertook the use of minimally invasive techniques for transperitoneal nephrectomy. Koyle et al. pointed out the direct advantages of laparoscopy in children, such as the small amount of retroperitoneal and abdominal fat compared to adults. Additionally, the size of pediatric patients allows for easier repositioning of the body after trocar placement, which improves exposure [13]. Furthermore, El-Ghoneimi in a retrospective study showed no significant differences in complications and operating time between patients undergoing laparoscopic nephrectomy and open nephrectomy. However, the laparoscopic group had a shorter hospital stay, which translates into greater comfort for pediatric patients and their caregivers [14].

With the development of kidney surgery, work was done on the possibility of performing laparoscopic adrenal procedures. Researchers observed less blood loss, shorter hospital stays, and reduced postoperative chemotherapy time in cases of neuroblastoma compared to open adrenalectomy [15,16].

Despite the intensive development of non-invasive techniques, there are still few reports regarding ureteroureterostomy (LUU). Gerwinn et al. proposed this method as an alternative to common sheath ureteral reimplantation (CSUR) in children with symptomatic duplicated kidneys. In a retrospective data analysis, a significantly shorter hospital stay was observed in patients undergoing LUU, while operating time and complication rates were similar for both groups [17].

Another issue concerning urinary tract procedures is ureteral reimplantation. To date, the largest review and meta-analysis results favored laparoscopy in terms of shorter hospital stays, less blood loss, and fewer wound infections. However, no significant difference was found in operating time and postoperative urinary tract infections, urinary retention, or hematuria [18]. Although enthusiasts of minimally invasive methods advocate for equal recognition of this method, it seems that according to current knowledge, the open method still remains the gold standard. Similar observations apply to bladder augmentation for the treatment of neurogenic bladder dysfunction. The first reports of attempts to perform this procedure were provided by Ehrlich and Gershman [19]. Subsequent researchers undertook the challenges of improving the method through completely intracorporeal suturing, hybrid robot-assisted operations, and large operations including nephrectomy, augmentation, and appendico-vesicostomy [20–22]. However, there is still a lack of evidence for the superiority of laparoscopy over the open method.

3. Laparoscopic Techniques Used in the Treatment of Urinary Tract Anomalies in Children

Including all available minimally invasive procedures used in pediatric urology would exceed the scope of this review. Therefore, we have decided to describe only some of them.

Retroperitoneoscopic heminephrectomy is mainly used for kidney duplication anomalies, especially when the upper segment is poorly functioning. A detailed description of the procedure was proposed by Taghavi and Mushtaq [23]. The advantages of this method include avoiding colon mobilization, thus reducing the risk of bowel injury; additionally, by not violating the peritoneum, postoperative pain can be reduced. Disadvantages of this approach include limited space and difficulty in anatomical orientation of the kidney. The procedure begins with a small incision, insertion of a balloon to expand the retroperitoneal space, a Hasson trocar, and working ports. The perirenal space is exposed by sweeping movements after incising Gerota's fascia. In subsequent stages, it is necessary to visualize both fragments of the duplicated system, divide the upper ureter, dissect the vascular pedicle at the hilum, and then, in the upper field, divide the distal ureteral stump. After assessing the renal capsule, resection of the upper fragment follows.

In cases of upper urinary tract obstruction, various laparoscopic approaches are used depending on the anatomical anomalies. In the report by Dzuhuma et al., several strategies are distinguished, namely dismembered pyeloplasty, pyeloplasty with renal sinus dissection, neo-PUJ anastomosis, primary ureterocalicostomy, pyeloureterostomy, and uretero-ureterostomy [24]. Researchers suggest that the transperitoneal approach allows for better identification of anatomical abnormalities and adaptation of the technique to the specific case, which translates into very good treatment outcomes. The key to success is accurate imaging showing kidney rotation, the presence of an extrarenal pelvis, and the thickness of the renal parenchyma.

When urinary tract anomalies occur in children, immediate urine drainage is often necessary. For many years, the established method was open cutaneous ureterostomy. The laparoscopic alternative is performed using three ports. The dilated ureter is easily identified, then mobilized and pulled out externally in a tension-free manner. In a study by Asimakidou et al., a three-month follow-up showed a satisfactory condition of the upper urinary tracts and no episodes of UTIs after laparoscopic intervention [25].

The open approach for pyeloplasty still remains the gold standard; however, an increasing number of reports in the literature provide good evidence for performing this operation by laparoscopic method. Using the Anderson-Hynes method, after entering the surgical field, perirenal fatty tissue is dissected, exposing the renal pelvis and ureter. It is important to visualize the site of urinary tract narrowing and its relationship to crossing vessels. The narrowed segment is resected, the ureter is incised obliquely to create a wide opening, while the renal pelvis is reduced with an "L"-shaped incision and sutured to the ureter. Adam and Smith observed modifications of the original procedure regarding the renal pelvis incision. These different approaches may result in variability in outcomes that have not yet been considered. To aid in understanding, documenting, describing, and comparatively evaluating dismembered pyeloplasty, a new classification has been proposed: ‘L’-shaped cut (original Anderson–Hynes pyeloplasty), ‘sector’ cut, ‘oblique renal pelvis’ cut, and ‘oblique pelvi-ureteric junction’ cut [26].

In cases of failed pyeloplasties, ureterocalicostomy is a salvage technique. As a primary procedure, it is used for ureteropelvic junction obstruction, but few such reports exist in the literature [27,28]. This method is chosen in cases of very small or deformed renal pelvis, poorly rotated kidney, horseshoe kidney, and giant hydronephrosis. During the procedure, the surgeon cuts the proximal part of the ureter and connects it directly to the renal calyx, most often the lower one. The biggest problem with the procedure is the thickness of the renal parenchyma, which must be thin enough to allow for proper anastomosis [29].

4. Application of Robotic Surgery in Upper Urinary Tract Anomalies

With the development of technology and the fascination with robotic surgery, this method began to be implemented in pediatric urology practice. The mentioned advantages such as tremor elimination, stable magnification, 3D vision, and precise suturing were an obvious incentive to attempt procedures using a robot. Every method adopted from adult surgery should consider anatomical and physiological differences. The main disadvantage of this technology is the disproportion between the size of the robot and all the instrumentation and the dimensions of the pediatric patient. Due to limited working space, various techniques can be used to facilitate work, such as positioning the robot arm in a more linear, less divergent configuration, to minimize the risk of damaging blood vessels or intestines, as well as using specialized cushions for proper positioning of pediatric patients [30].

The additional increased dexterity of the robot can be particularly beneficial in pediatric surgery, where the smaller body size of patients sometimes poses an anatomical barrier with a classical approach. For many centers, financial issues remain a limitation to the development of the robotic method. The initial cost of purchase, maintenance of the robot itself, costs of disposable equipment for the procedure, as well as personnel training, pose an obstacle for many medical centers [31].

Robotic surgery, like laparoscopy previously, remains a new technique requiring an appropriate training program. Analyzing the learning curve, it turns out that learning its operation can be faster due to the intuitive, symmetrical movement of the equipment, imitating the surgeon's wrists. Additionally, studies have shown that individuals with prior experience in laparoscopy achieve good results faster when using the robot. It is important that the entire surgical team is familiar with the procedure, which translates into greater efficiency, especially in more complex operations [32].

According to reports by Cundy et al., the most popular procedure in the pediatric population using robotic surgery is pyeloplasty [33]. The previously described laparoscopic method involves many technical difficulties that the robotic option avoids. Khoder et al. observed that robotic pyeloplasty is associated with low morbidity, satisfactory surgical and functional outcomes with no significant differences in complication rates compared to the laparoscopic approach [34].

Due to doubts about the method's use in infants, Kafka et al. conducted a prospective safety evaluation of robot-assisted pyeloplasty in children weighing <10 kg, comparing its results with a matched cohort of patients undergoing traditional open pyeloplasty, extracted from a retrospective database. The analysis showed no statistically significant differences in treatment outcomes or complication rates [35]. To further reduce morbidity and simplify postoperative care, Fichtenbaum et al. performed outpatient robotic pyeloplasty (RP) and robotic ureteroureterostomy (RUU) without ureteral stents, drains, or urethral catheters. This eliminated the need for re-hospitalization in pediatric patients for stent removal, which was often an argument among proponents of open surgery [36]. A literature review by Mizuno et al. showed that RP resulted in shorter operating times and shorter hospital stays than classical surgery. RP was also associated with comparable or lower complication rates and comparable or higher success rates compared to open surgery as well as laparoscopy [37].

In the case of total or partial nephrectomies, the open approach still dominates. However, in recent years, there has been a significant surge in interest in minimally invasive techniques. Although most are currently performed using laparoscopic techniques, an increasing number of descriptions of robot-assisted procedures are appearing in the literature [38]. Based on clinical experience, Antar et al. suggest that robotic partial nephrectomy is a feasible minimally invasive procedure that can be safely performed in pediatric patients with small kidney masses. However, they emphasize the importance of cooperation with surgeons experienced in adult robotic methods and technical differences, such as the need to place all ports in the midline to ensure adequate distance between trocars [39].

In an analysis by Calvillo-Ramirez et al., minimally invasive techniques, including laparoscopic and robotic, were collectively compared to open surgery. A pooled analysis of postoperative complications showed no statistical significance between the groups (OR 0.80; 95% CI: 0.33–1.94; $p = 0.62$), suggesting comparable risk. A significant advantage of minimally invasive methods was shown in significantly lower opioid consumption after procedures (mean difference [MD] −1.21; 95% CI: −1.75 to −0.67; $p < 0.0001$), shorter hospital stay (MD −2.16 days; 95% CI: −3.15 to −1.18; $p < 0.0001$), and lower estimated blood loss (MD −16.87 ml; 95% CI: −22.33 to −11.41; $p < 0.0001$) [40].

5. Conclusions

The application of minimally invasive surgical techniques in pediatric urology has evolved from purely diagnostic indications to advanced therapeutic procedures. With the expansion of specialized knowledge among pediatric urologists and their skills in performing laparoscopic procedures, there has been dynamic progress in their applications, including highly complex procedures on the upper and lower urinary tracts. These procedures often provide patients with fewer postoperative scars, better wound healing, and shorter hospitalization than conventional open methods. Due to comparable results from numerous studies comparing laparoscopy to classical methods, the choice of minimally invasive treatment has become the gold standard for many conditions. In the case of robotic surgery, intracorporeal suturing guarantees real-time robotic arm movement with an increased degree of freedom, 3D vision with tremor elimination, which no other method provides. Continuous improvement of equipment and evolution of procedures can provide alternative treatment methods, leading to improved patient care and quality of life.

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Check: JM, JŻ
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Investigation: Resources: JZ, MM, MB
Data curation: JZ, JK
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