

Review Article

Advances in paediatric urology: the role of minimally invasive surgery and emerging technologies in personalized treatment approaches for congenital urological disorders

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Abstract: Minimally invasive surgery (MIS) and emerging technologies have completely changed pediatric urology, enabling more precise, less invasive, and increasingly personalized treatment of congenital urinary system diseases. This article reviews the contemporary progress in the fields of laparoscopic surgery, robot-assisted surgery, artificial intelligence (AI), three-dimensional (3D) imaging and printing, tissue engineering and regenerative medicine, and comprehensively evaluates the contribution of these technologies to personalized treatment strategies. Literature retrieval covers relevant studies published in major biomedical databases between 2000 and 2025. Existing evidence shows that compared with traditional open surgery, laparoscopic and robot-assisted surgery have good clinical effects, reducing postoperative complications, shortening hospital stays and improving cosmetic outcomes. Artificial intelligence-based technology is increasingly improving the accuracy of diagnosis, risk stratification and clinical decision-making, while advanced imaging technology and patient-specific three-dimensional modeling have further optimized surgical planning and operation accuracy. Tissue engineering and regenerative medicine provide promising future solutions to complex reconstructive challenges, although most applications are still in the research stage. The integration of these innovations helps to formulate personalized treatment plans according to the characteristics of anatomy, function and disease specificity, and promote the transformation of pediatric urology to precision medicine. Despite the remarkable progress, factors such as high implementation costs, the need for specialized training, ethical concerns, and a lack of large-scale validation studies still limit its wide application. Continuous technological development, multi-center clinical verification and standardized implementation path are crucial to maximize clinical benefits and improve the long-term prognosis of children with congenital urinary system diseases.

Keywords: Minimally invasive surgery, pediatric urology, artificial intelligence, three-dimensional printing, robotic surgery, personalized medicine, tissue engineering, regenerative medicine, surgical innovation, precision medicine

Introduction

Congenital urinary system diseases are an important part of pediatric surgical diagnosis and treatment. If they are not identified and properly handled in time, they may lead to repeated infections, urinary disorders, abnormal bladder function, kidney injury or chronic health problems. Common diseases include prenatal hydronephrosis, Ureteropelvic Junction Obstruction (UPJO), vesicoureteral regurgitation (VUR), posterior urethral valve (PUV) and

hypospadias. Prenatal ultrasound and structured post-natal assessment are conducive to early detection, but there remains significant variability in disease severity and clinical course. In recent decades, minimally invasive surgery (MIS) has been increasingly used in pediatric urology, including laparoscopic surgery, robot-assisted surgery and transurethral techniques, combined with traditional open reconstruction. The development of these methods reflects the progress of instruments and imaging technology, and a greater emphasis on

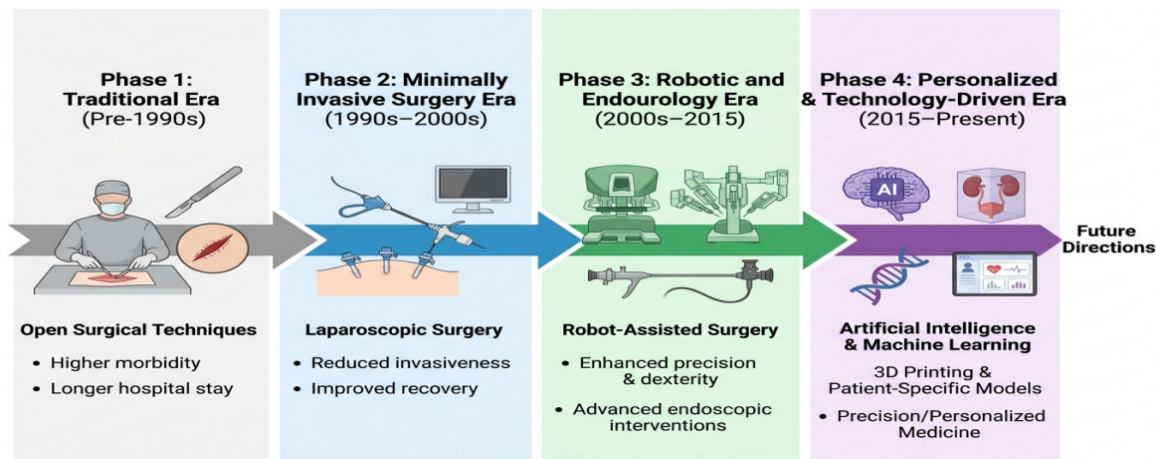


Figure 1. Evolution of pediatric urology from conventional open surgery to technology-enabled personalized care. The figure illustrates major milestones in the development of pediatric urological surgery, highlighting the transition from open surgical procedures toward minimally invasive approaches and technology-driven personalized treatment strategies.

reducing perioperative complications while ensuring durable long-term functional outcomes [1-7].

Laparoscopic pyeloplasty has been extensively evaluated for the treatment of UPJO. For properly screened children, it has a high success rate and short recovery time, which is superior to traditional open surgery. Robotic-assisted systems offer enhanced dexterity, tremor filtration, and three-dimensional visualization, which is conducive to the in vivo suture operation during complex reconstruction. For some specific diseases, such as high-grade VUR and PUV, transurethral diagnosis and treatment are still at the core, because such treatment can be carried out through the urinary system, and the external trauma to the patient is relatively small. At the same time, emerging technologies are reshaping the clinical practice of pediatric urology. Artificial intelligence (AI) and machine learning are being used to assist in diagnosis, image interpretation, risk stratification and prognosis prediction, while patient-specific three-dimensional (3D) modeling aids in comprehending complex anatomy and optimize surgical planning. Tissue engineering has also entered the early clinical transformation stage in the field of reconstructive urology. Although the application of regenerative medicine is still in the research and exploration stage, it has not yet become a conventional treatment method. These advances are consistent with the overall concept of precision

medicine, that is, the formulation of individualized treatment plans according to the anatomy, function and clinical characteristics of patients [3, 5, 7-16].

Despite the rapid development of minimally invasive surgery and emerging technologies, the evidence base supporting the integration of specific surgical techniques with new technologies remains fragmented. Robotic surgery, artificial intelligence, advanced imaging technology and regenerative medicine have significant differences in maturity, clinical indications and the quality of supporting evidence. Therefore, this article aims to critically integrate the existing evidence of minimally invasive surgery and emerging technologies in the field of childhood urology, and explore how these methods can advance personalized treatment of congenital urinary system diseases. The focus of the review includes clinical applications, comparative results, challenges in implementation, and areas that need further verification [5, 6, 12].

Figure 1 describes the evolution of pediatric urology from traditional open surgical techniques to minimally invasive and technology-driven personalized care. The timeline highlights key transitions from open surgery to laparoscopic and robotic-assisted approaches, followed by the integration of emerging technologies such as artificial intelligence, three-dimensional printing, and precision medicine.

These advancements have contributed to improved surgical outcomes, reduced morbidity, and the development of individualized treatment strategies for congenital urological disorders in pediatric patients.

Literature search strategy

To improve transparency, a targeted literature search was conducted using PubMed, Embase, Scopus, and Web of Science databases. Relevant studies published between January 2000 and March 2025 were identified using combinations of the following keywords: “pediatric urology”, “minimally invasive surgery”, “laparoscopy”, “robotic surgery”, “artificial intelligence”, “three-dimensional printing”, “personalized medicine”, “tissue engineering”, “ureteropelvic junction obstruction”, “vesicoureteral reflux”, and “congenital urological disorders”. Original research articles, systematic reviews, meta-analyses, clinical guidelines, and landmark technological studies published in English were considered. Articles focusing exclusively on adult populations, conference abstracts, and duplicate reports were excluded. The selected literature was narratively synthesized to provide a comprehensive overview of current advances and future directions in pediatric urological care.

Minimally invasive surgery (MIS) conceptual overview

MIS has revolutionized the field of pediatric urology by providing a feasible alternative to traditional open surgery. In the past two decades, the application of minimally invasive technology has grown exponentially, mainly due to its significant advantages in reducing surgical trauma, shortening recovery time and improving cosmetic outcomes, which are especially important for children. Unlike traditional open surgery, minimally invasive technology adopts small incisions, special instruments and advanced visualization equipment to achieve clinical efficacy comparable or even better than traditional surgery while bringing less physiological burden to patients. In pediatric urology, minimally invasive techniques represent a collection of surgical approaches aimed at minimizing tissue damage and maintaining the effectiveness of surgery. The main methods include laparoscopic surgery, robot-assisted surgery and endoscopic urological sur-

gery. Although these methods differ in instrumentation, technical complexity and clinical application, their common goal is to minimize the incidence of perioperative complications [5-10, 17].

Traditional laparoscopic surgery uses small incisions, cameras and special instruments to operate in the body cavity under a magnified field of view. On this basis, robot-assisted surgery provides movable instruments, motion scaling, tremor filtering and high-definition three-dimensional visualization functions. These characteristics are advantageous for reconstructive surgery that requires fine separation and suture in children's limited anatomy. In contrast, intra-abdominal urinary system surgery is performed through the natural urinary tract, which is especially suitable for diagnosis and specific treatment intervention [5-7].

MIS major modalities

Laparoscopic surgery: Laparoscopic surgery is one of the earliest minimally invasive techniques used in pediatric urology, and it is still widely used in pyeloplasty and nephrectomy. Its main perioperative advantages include smaller incisions, reduced postoperative discomfort, shorter hospitalization time and good cosmetic outcomes. Prospective studies and meta-analysis of ureteroplasty in children show that the success rate of laparoscopic repair in properly selected patients is comparable to that of open surgery. However, the learning curve of traditional laparoscopic surgery is steeper, especially in infants and young children, because intracavitary sutures and instrumentation must be completed in a limited working space [6, 8-10].

Robot-assisted surgery: Robot-assisted surgery is a major progress in the field of minimally invasive reconstruction in children. The modern platform is equipped with movable instruments, motion zoom function, tremor filtration system and high-definition three-dimensional visualization technology, which helps to achieve fine anatomy and intracavity suture. Pediatric surgical applications now include ureteroplasty, ureteral reimplantation, nephrectomy or seminephrectomy, and some complex bladder or ureter reconstruction surgeries. Compared with traditional laparoscopy, robotic assistance can enhance surgeon efficiency and may shorten

the technical learning curve of intracavity reconstruction, but these advantages must be balanced with the cost, equipment accessibility and the demand for professional team training [5-7, 18].

Endourology: Endourology is a minimally invasive surgical subspecialty performed through the urinary system using endoscopic tools, which is usually used to treat diseases such as VUR and PUV. Operations such as cystoscopy, valve ablation and endoscopic injection therapy have the advantages of low invasiveness, short recovery time and low complication rate. One of the advantages of endourology is that there is no need for an external incision, thereby significantly reducing postoperative discomfort and hospital stay. However, this method may not be applicable when the anatomy is complex and reconstruction surgery is required [2, 3, 11].

Benefits of minimally invasive surgery and open surgery

The transformation from open surgery to minimally invasive surgery is mainly due to the advantages of the perioperative period, such as smaller incisions, reduced postoperative analgesic requirements, shorter hospitalization time and faster recovery. At the same time, mature reconstruction surgery still maintains a high success rate. These advantages are especially obvious in pediatric ureteroplasty and other operations. However, the degree of benefit varies depending on the surgical method, the age of the patient, the path of the medical institution and the experience of the surgeon; therefore, the minimally invasive approach should not be understood as evidence that the long-term efficacy is better than the traditional method under all indications [8-10, 18].

Limitations and challenges

MIS also has important limitations. The procurement and operation costs of robot platforms are high, and advanced minimally invasive surgery requires special equipment, trained personnel and a sufficient number of cases to maintain operational proficiency. The smaller anatomical workspace in children may limit port placement and operating angle of the puncture needle, and the learning curve may also increase operative time during the imple-

mentation of a new program. Therefore, simulation training, systematic training and forward-looking result monitoring are particularly important when introducing new technologies. These economic and technical obstacles may also lead to a gap between resource-rich third-level centers and institutions lacking advanced equipment [7, 19-22].

In pediatric patients, the smaller anatomical workspace and the demand for appropriately sized instruments make minimally invasive surgery more technically challenging, especially in infants and young children. The continuous development of platforms and instruments is solving some of these limitations, but the patient's body size is still an important factor affecting the feasibility of surgery [7, 17, 18].

Patient selection, perioperative considerations, and safety

Patient selection is a key factor in determining the safety and value of pediatric minimally invasive urological surgery. There is significant anatomical variation among pediatric patients, from newborns to adolescents. The technique, which is relatively simple for older children, may require a higher level of technology for babies. The size of the body will affect port placement, the angle of operation, the collision of the instrument, insufflation pressures and the feasibility of in vivo suture. In addition, the anatomy of disease-specificity needs to be considered. For example, in UPJO, factors such as vascular crossing, renal pelvis, previous surgical history or congenital malformation may affect the complexity of reconstruction surgery. In VUR, backflow level, breakthrough febrile urinary tract infections, bladder and bowel dysfunction, kidney scars and a history of previous endoscopic treatment may affect the choice between observation, endoscopic injection or surgical re-implantation. Therefore, minimally invasive surgery should be regarded as part of a broader decision-making framework, rather than as an isolated technical preference [2, 3, 23].

Age-appropriate anesthesia and physiological considerations are equally important. Intra-abdominal emphysema may affect ventilation and venous return, so insufflation pressures must be carefully selected in infants. Body fluid management, body temperature regula-

tion, body position placement and prevention of stress-related injuries all require close cooperation between the surgical team and the anesthesia team. Although modern laparoscopy and robotic surgery are generally well tolerated among appropriately selected pediatric patients, patient safety still depends on adapting the adult principle to the physiological characteristics of children. Preoperative planning should identify children with cardiopulmonary complications, renal dysfunction, active infection or a history of abdominal surgery, which may need to be additionally optimized or adjusted. The threshold for conversion to open surgery should be guided by safety and efficacy, rather than just pursuing minimal trauma to complete the operation [7, 17].

The choice of surgical method should also be determined according to the expected reconstruction task. For surgeons with advanced laparoscopic suturing skills, traditional laparoscopic surgery may be efficient and economical; while robotic assistance can lower the technical difficulty and improve the efficiency of operation in the process of fine reconstruction. When the lesion can be treated through the natural path of the urinary tract, endoscopic management is particularly attractive, but repeated use of instruments or restricted access may offset the advantage of avoiding external incisions. Therefore, the individualized treatment plan should comprehensively consider the possibility of success of a single operation, the necessity of postoperative drainage or stent placement, the possibility of staged treatment and the consequences of failure. The goal is not only to reduce the size of the incision, but also to achieve a lasting correction effect with the lowest cumulative burden [7, 18].

The perioperative planning should clearly include the preparation of postoperative care. Children and their caretakers need to be clear about the expected pain, catheter or stent, movement restrictions, warning signs of infection or obstruction, and follow-up arrangements. The standardized process helps to reduce the differences in pain relief, rehydration, activity recovery, discharge time and communication. When comparing minimally invasive surgery and open surgery, these factors related to the process should be recognized, because the shortening of hospitalization time

may be due to differences in surgical techniques and institutional rehabilitation programs. Long-term efficacy studies of pyeloplasty show that the differences in the perioperative period should be comprehensively evaluated in combination with lasting functional results, rather than being viewed in isolation [23]. Safety assessment also includes the understanding of the learning curve. The initial experience of using the new platform may lead to prolonged surgery time and more conservative case selection is required. Through simulated training, phased certification, mentor guidance and team drills, risks in the implementation process can be reduced. Hospitals that introduce robotic pediatric urology should identify which cases are suitable for use in the early learning stage, and make forward-looking records of the operation time, referral, complications, re-hospitalization and reoperation. This is especially important because serious complications are relatively rare and may not be detected in time in small single-center data. Therefore, collaborative databases and multi-center quality improvement projects can reflect security and effectiveness more reliably than isolated institutional experience [7, 21, 22].

Finally, the treatment choice should consider the family-centered effect. Children may pay more attention to smaller scars and returning to school or returning to normal activities as soon as possible, while parents may pay more attention to the persistence of the treatment effect, reduce the number of trips or avoid repeated anesthesia. These priorities may vary from family to family and may be influenced by distance from specialist care, socio-economic resources, and past treatment experience. Shared decision-making should clearly explain the advantages and limitations of each reasonable treatment plan, but it should not imply that the latest technology is necessarily superior to other solutions. In this sense, the most personalized plan is to integrate anatomy, physiology, disease severity, expected long-term function, institutional professional ability and family preferences into a coherent plan.

Clinical applications of minimally invasive surgery in pediatric urology

Ureteropelvic junction obstruction (UPJO)

UPJO is one of the most common reconstruction indications in pediatric urology. Open dis-

membered pyeloplasty remains the effective reference standard, but laparoscopy and robot-assisted pyeloplasty are now widely used in professional centers. Prospective research and meta-analysis show that minimally invasive ureteroplasty can achieve a high success rate comparable to open repair, and has potential advantages in terms of postoperative pain, hospital stay and cosmetic outcomes. Long-term comparison data also shows that the functional results after robot-assisted repair are long-lasting. Therefore, when choosing an open, laparoscopic or robot-assisted method, the patient's size, anatomical complexity, previous surgical history, surgeon's experience, institutional resources and family preferences should be taken into account, rather than assuming that a certain technical platform is generally superior to others [7-10, 23].

Vesicoureteral reflux (VUR)

VUR is an important index for the treatment of the urinary system in some children. Endoscopic injection of bulking agents can be performed on an outpatient or short-stay basis, and there are fewer postoperative complications, but its efficacy depends highly on the reverse flow degree and the patient selection criteria. Evidence from meta-analysis and large-scale cohort studies shows that the healing rate of high-risk reflow patients is lower and may increase after repeated injections. Given that factors such as spontaneous resolution, recurrent febrile UTIs, renal scarring, bladder-bowel dysfunction, and reflux grade influence management, endoscopic treatment should be included in a broader risk-based strategy, rather than as a common preferred treatment method [2, 11, 24, 25].

For severe VUR, repeated fever infection, kidney risk or failure of conservative treatment and endoscopic treatment, ureteral reimplantation can be considered. Open reimplantation has been widely recognized, while laparoscopy and robot-assisted technology can achieve the principle of reconstruction in experienced centers through minimally invasive methods. Decision-making should comprehensively consider the severity of backflow, bladder function, past treatment history, patient's size, surgeon's experience and the possibility of long-term success of a single operation [2, 7, 18].

Posterior urethral valve (PUV)

PUV is one of the main causes of congenital lower urinary tract obstruction in boys, which may compromise renal and bladder function. The initial treatment includes bladder drainage and stabilization when necessary, followed by endoscopic valve ablation if the anatomical structure and the patient's body size allow. Endoscopic treatment can alleviate anatomical obstruction and have fewer external complications, but successful ablation cannot completely eliminate the risk of persistent bladder dysfunction, repeated urinary system problems or progression of chronic kidney disease. Therefore, it is very important to monitor kidney function, bladder function, growth and development, blood pressure and urination symptoms for a long time [3].

Hypospadias and its repair

Unlike many other cases discussed in this review, the definitive repair of hypospadias still relies mainly on open reconstruction surgery, rather than conventional laparoscopic or robotic minimally invasive surgery. The anatomy of proximal hypospadias varies greatly, and the surgical effect depends on factors such as the quality of the urethral plate, the degree of ventral curvature, tissue availability and the selected reconstruction strategy. Comparative studies of proximal hypospadias repair report high reoperation and fistula rates, so individualized selection between single-stage and phased techniques is supported. Therefore, at present, robot-assisted technology should be regarded as a research method in the reconstruction of hypospadias, rather than an alternative to traditional repair [4].

Comparative analysis of different minimally invasive surgery methods

Comparative studies carried out through different minimally invasive surgery methods highlight the advantages and limitations of each method. Laparoscopic surgery is cost-effective and widely used, but may be limited by technical complexity. Robot-assisted surgery performs better in terms of operation engineering, accuracy and learning efficiency, but it is expensive and in limited supply [7, 18, 19].

Long-term outcomes and procedure selection in UPJO

Long-term success is particularly important when using minimally invasive techniques to treat UPJO, because the seemingly smooth perioperative process itself does not guarantee lasting functional benefits. Follow-up should comprehensively evaluate the symptoms, the dynamic changes of ultrasound of hydronephrosis, renal function examination when clinically necessary, and whether another operation is required. A controlled study with long-term follow-up in children showed that the success rate of robot-assisted laparoscopic ureteroplasty and open ureteroplasty was equivalent in terms of pain, hydronephrosis and renal function. Although the postoperative hospitalization time of robotic surgery was shorter, the operation time was longer. These results support the following view: the choice of surgical method should be decided according to the patient's age and size, anatomy complexity, surgeon's experience, medical institution resources and family wishes, rather than assuming that a certain technique is generally superior to other methods [23].

Robotic surgery is particularly attractive for reconstructive surgery, because movable instruments and magnified three-dimensional visualization technology help to complete suture operations in a narrow space. However, the potential advantages must be comprehensively evaluated in combination with cost, reach and learning curve. A review of robotic surgery in children's urology points out that its indications are constantly expanding, including pyeloplasty, ureteral reimplantation, kidney stone surgery, partial nephrectomy, bladder enlargement, bladder neck reconstruction and continent catheterizable stomas. At the same time, it emphasizes the need to carry out a larger-scale pre-Prospective research, cost analysis and learning curve research. This evidence supports the selective implementation of relevant technologies in centers with a sufficient number of cases, a well-trained multidisciplinary team, and the ability to monitor long-term follow-up results [7].

When making personalized choices between open surgery, laparoscopic surgery, robot-assisted surgery and transurethral surgery, the

cumulative treatment burden should also be considered. For children, repeated anesthesia, stent or catheter discomfort, postoperative imaging, absence from class, caregiver burden, and the possibility of staged surgery may affect the preferred treatment strategy, even if the technical success rate is comparable. Minimally invasive surgery may help reduce incision-related complications, but should not affect the durability of reconstruction or lead to unnecessary repeated interventions. Therefore, joint decision-making should include the expected success rate, the uncertainty of long-term prognosis, the demand for postoperative equipment, the recovery process and the professional experience of each center.

Transurethral technique is the least invasive treatment method, which is especially valuable when pathological conditions can be directly treated through the urinary system, such as endoscopic treatment of VUR and PUV. However, its applicability depends on the specific indications, and complex reconstructive anatomy may require laparoscopy, robotics or open surgery. Therefore, in the field of pediatric urology, the best treatment method should be selected according to the severity of the disease, anatomical structure, expected durability, surgeon expertise, and institutional capabilities, not just based on the degree of invasiveness [2, 3, 11, 18].

Minimally invasive surgical methods show unique and complementary advantages in different clinical parameters. As shown in **Figure 2**, robot-assisted surgery has higher accuracy and enhanced visualization, which is especially suitable for complex reconstructive surgeries. In contrast, laparoscopic technology has balanced advantages and disadvantages, high success rate and low relative cost, but higher requirements for technical level. Although transurethral interventional treatment is limited to specific indications, it has the least trauma, the least postoperative discomfort and rapid recovery. These differences highlight the importance of choosing the appropriate surgical method according to the individual characteristics of the patient, the complexity of the disease and the available resources [7, 18, 19].

Table 1 systematically outlines the main clinical applications of minimally invasive surgery technology in pediatric urology, focusing on

Minimally invasive and precision paediatric urology

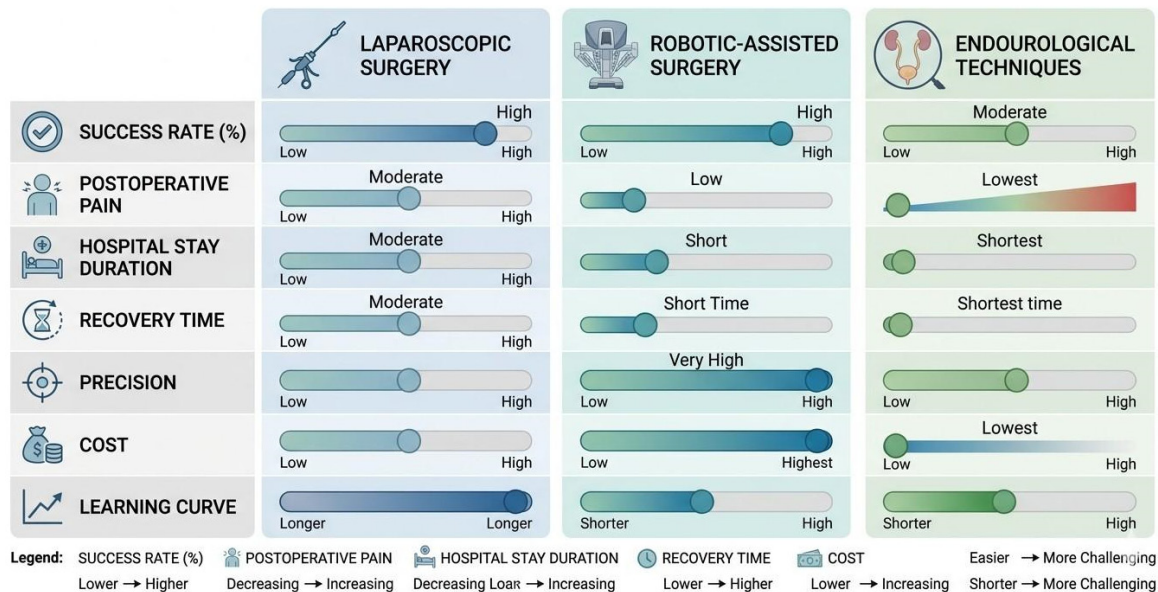


Figure 2. Comparative characteristics of minimally invasive surgical modalities in pediatric urology. Comparison of laparoscopic, robotic-assisted, and endourological approaches according to surgical precision, invasiveness, recovery profile, technical complexity, and clinical applicability.

Table 1. Clinical applications of minimally invasive surgery in pediatric urology

Condition	MIS Technique	Indication	Advantages	Outcomes
Ureteropelvic Junction Obstruction (UPJO)	Laparoscopic/Robotic pyeloplasty	Obstruction with impaired drainage	High precision, reduced morbidity	High success rates (>90%), improved renal function
Vesicoureteral Reflux (VUR)	Endoscopic injection/Robotic reimplantation	Moderate to high-grade reflux	Minimally invasive, shorter hospital stay	Good reflux resolution, low complication rates
Posterior Urethral Valves (PUV)	Endoscopic valve ablation	Bladder outlet obstruction	Minimally invasive, rapid recovery	Improved urinary flow, preserved renal function

commonly used methods, indications and relevant clinical results reports. In different cases such as UPJO, VUR and PUV, minimally invasive techniques have shown a high success rate and significantly reduced perioperative complications. Laparoscopy and robot-assisted technology are mainly used in reconstructive surgery, which can provide higher accuracy and more lasting treatment; while transurethral interventional treatment is more popular in appropriately selected cases because of its minimally invasiveness and rapid recovery. In general, these research results further confirm that minimally invasive surgery (MIS) is increasingly prominent as a multifunctional and effective means of treating various diseases of the urinary system in children.

Pediatric urology-based emerging technology

Emerging technologies are increasingly complementing diagnostic and therapeutic modalities

of minimally invasive pediatric urology. Artificial intelligence is being used in image analysis, prediction and decision-making support; three-dimensional modeling and printing technology can provide patient-specific presentation for complex anatomical structures; and tissue engineering provides a potential path for reconstructive treatment, helping to reduce or avoid the use of non-urological tissues. However, these technologies are still at different stages of clinical maturity. Artificial intelligence and three-dimensional modeling still need further forward-looking verification, while the construction technology of recycled materials is still in the research stage. Therefore, their most suitable role is to assist rather than replace individualized clinical judgment [12-15] (Table 2).

Artificial intelligence and machine learning

Artificial intelligence and machine learning are getting more and more attention in the research

Table 2. Emerging technologies in pediatric urology: applications, advantages, and limitations

Technology	Applications	Advantages	Limitations
Artificial Intelligence (AI)	Diagnosis, risk prediction, decision support	Improved accuracy, automation, data-driven decisions	Data dependency, bias, need for validation
3D Printing & Modeling	Preoperative planning, patient-specific anatomy	Enhanced visualization, surgical simulation	Cost, time, technical expertise required
Advanced Imaging (MRI/CT with reconstruction)	Anatomical assessment, surgical planning	High-resolution detail, improved diagnosis	Radiation exposure (CT), cost
Robotic Surgery	Complex reconstructive procedures	Precision, dexterity, improved ergonomics	High cost, training requirements
Tissue Engineering	Bladder reconstruction, urethral repair	Potential for regenerative solutions	Experimental stage, regulatory challenges

ch of pediatric urology. These methods can identify the complex association between imaging data and clinical data, and have potential application value in diagnosis, risk prediction, workflow support and outcome modeling. However, pediatric urology data is usually small in scale, heterogeneous and institution-specific. It is essential to carry out external verification and careful evaluation of the generalization ability of the model before clinical application [12, 26, 27].

Diagnosis: Image analysis technology based on artificial intelligence is expected to improve the consistency and efficiency of the structural evaluation of pediatric urology, including conditions associated with hydronephrosis. This is of great clinical significance, because traditional grading systems (e.g., the SFU grading) have good intra-observer but only modest inter-observer reliability. Artificial intelligence may eventually provide repeatable quantitative features or decision support, but the current evidence in the field of pediatric urology is still in the development stage and should not be regarded as the basis for autonomous diagnosis [12, 28].

Risk prediction: In addition to diagnosis, artificial intelligence and machine learning models can also support risk stratification and prognosis prediction by integrating demographics, imaging, laboratory and longitudinal clinical information. Potential applications include assessing the probability of disease progression, spontaneous remission or treatment failure, and identifying patients who may benefit from closer monitoring or early intervention. Before affecting the treatment threshold, such models should be evaluated for calibration, external effectiveness and clinical practicality [12, 26, 29].

In diseases such as VUR and UPJO, verified predictive models may eventually help identify children with high-risk progressions, complications or treatment failures, thus guiding monitoring intensity and intervention timing. However, at present, the evidence of artificial intelligence in pediatric urology is still in the development stage, and such models should be used as a supplement to the existing clinical and functional assessment, rather than a substitute [12, 26].

Decision-making support: The artificial intelligence-based clinical decision-making support system can combine patient data with evidence-based medical information to assist in diagnosis and treatment selection. In the field of pediatric urology, its greatest value is reflected in complex situations, that is, when there are many reasonable management strategies. However, the performance of decision-making support must be evaluated in the real clinical workflow, and the algorithm recommendation should always be subject to the judgment of the specialist, the anatomical and physiological characteristics of individual patients, and family preferences [12, 26, 30].

The application of artificial intelligence in clinical practice has also raised a series of important methodological and ethical issues. When the data quality is poor or the population used for training is different from the deployment population, the model may fail. Algorithm bias may lead to uneven performance among different population groups, and the use of large-scale clinical data sets brings challenges in privacy, governance and informed consent. Therefore, transparent reporting, external verification, continuous performance monitoring and clear attribution of responsibility are the

prerequisites for achieving responsible application [30-32].

Three-dimensional printing and advanced imaging

Three-dimensional printing and advanced imaging technology can transform cross-sectional data into digital or physical personalized models of patients, thus improving the visualization of complex anatomical relationships. In pediatric urological surgery, these models have been used to assist in the planning of specific and complex kidney diseases and reconstructive surgeries. When traditional two-dimensional image review cannot fully convey the spatial relationship related to surgery, the value of these models is particularly prominent [13, 33].

Preoperative planning: For complex pediatric urological surgery, high-resolution CT or MRI combined with three-dimensional reconstruction technology is increasingly widely used in preoperative planning. Virtual models or physical prints can be generated through digital segmentation, so that surgeons can visualize the anatomy, predict technical difficulties and discuss surgical strategies before entering the operating room. The professional guidance of medical 3D printing emphasizes suitable clinical indications, verified segmentation processes and quality assurance. Evidence of surgical application shows that the technology has potential advantages in preoperative planning and communication, although production time, cost and accumulation of clinical benefits are still important considerations [13, 33-35].

Individualized modeling: Individualized modeling is a practical embodiment of personalized surgical planning. The model based on the image data of pediatric patients can be used for multidisciplinary discussions, surgical simulations, resident training, and communication with patients and their families. The diagnosis and treatment process of the pediatric urinary system has proved that it is feasible to create accurate digital and printed models for complex cases. However, due to factors such as the professionalism of segmentation technology, image quality requirements, production time and cost, the wide application of this technology is still limited and should only be used in those cases that are expected to change the diagnosis or treatment method [13, 35].

Clinical verification of artificial intelligence and three-dimensional modeling

The clinical significance of artificial intelligence in pediatric urology depends on whether its computing performance can be transformed into better decision-making and improved treatment results. Pediatric data sets are usually smaller and more heterogeneous than adult data sets. Even in tertiary medical centers, congenital diseases may be rare. This may lead to problems such as overfitting, class imbalance and poor external generalization ability. A recent review of the application of artificial intelligence in pediatric urology points out that AI has application potential in image analysis, diagnosis, prediction and decision-making support, but also emphasizes the need for full verification before formal clinical deployment. Therefore, the model evaluation should not only include distinguishing indicators, but also cover calibration, subgroup performance, external verification, and the clinical consequences of false positive and false negative predictions [12, 30]. Therefore, artificial intelligence should be used as an auxiliary decision-making tool, rather than completely replacing the professional judgment of pediatric urologists. For example, in hydronephrosis, automatic image analysis may help improve repeatability or quantify visually difficult-to-judge characteristics, but treatment interventions still depend on factors such as symptoms, follow-up images, renal function data, history of urinary tract infection and age. Similarly, the model for predicting the progression of the disease or the success of surgery should be interpreted in combination with the child's anatomy and family preferences. Explainable outputs, confidence estimates, and transparent identification of influential predictors are safer and more meaningful in clinical practice and more meaningful communication with family members [12, 30].

Three-dimensional modeling provides a complementary personalized means by transforming cross-section images into intuitive individualized presentation. Silvestro and his colleagues described a pediatric urinary system workflow using multi-stage enhanced contrast imaging to generate accurate digital and printed models for complex surgical planning. When anatomical abnormalities cause conventional two-

dimensional image review to be unable to meet the needs, such models may be of practical value, such as in some reconstructive surgery cases and complex renal lesions. However, before routine implementation, it is still necessary to consider the segmentation time, software and printing costs, image quality requirements, and the technical expertise of professionals [13].

Therefore, the future evaluation of artificial intelligence and three-dimensional modeling should focus on clinical practicality, not just technical novelty. Effective evaluation indicators include changes in surgical strategy, decision-making confidence, operation time, incidence of complications, the need for additional imaging, the understanding of medical staff, and cost-effectiveness. Prospective multicenter verification is particularly important because the performance of tools developed by the same institution may be different when the imaging protocol, referral model or patient demographic structure changes. The goal is to identify technologies that can bring measurable value to clinical care and avoid thinking that more complex digital workflows necessarily mean a higher degree of personalization [12, 13, 35].

Tissue engineering and regenerative medicine

Tissue engineering and regenerative medicine are promising but still developing fields in reconstructing urology. A landmark clinical study implanted autologous tissue engineering bladder constructs into the bodies of children and adolescents with poor bladder performance and need for cystostomy, proving the feasibility of the cell implantation stent strategy. However, due to the small sample size and subsequent challenges in achieving lasting functional benefits, artificial bladder replacement is still not considered a conventional standard treatment. The current research continues to focus on biomaterials, cell origin, vascularization, nervation and functional integration [14, 36].

Progress of the experiment

Regenerative medicine methods are also being used in urethral and other urinary system reconstruction. The clinical experience of tissue engineering autologous urethra shows that

it is feasible to transform, and the progress of stent design and three-dimensional bioprinting technology provides experimental strategies for the production of patient-specific tissues. Important obstacles include vascularization, mechanical and functional durability, repeatable manufacturing, regulatory approval, long-term safety and cost issues. These limitations explain why most regenerative medicine applications are still in the research stage despite significant progress in biomaterials and tissue engineering [36-40].

Personalized medical treatment in children's urology

Personalized medicine has become an increasingly important framework in modern healthcare. Unlike the same intervention for all patients with the same diagnostic label, precision medicine selects the most appropriate treatment strategy by integrating the biological, anatomical, physiological and clinical characteristics of individuals. This concept is particularly important in children's urology, because congenital abnormalities vary greatly in terms of anatomy, course development, kidney risk, functional effects and response to treatment. When minimally invasive technologies and emerging technologies can improve patient screening, surgical planning or long-term risk assessment, they help to achieve personalized treatment, not just increase technical complexity [15, 16, 41, 42].

Definitions and principles

Precision medicine can be defined as tailoring prevention, diagnosis, treatment, and follow-up to the characteristics of individual patients or subgroups. In pediatric urology, this includes not only molecular or genetic data, but also anatomical details, age and growth and development, kidney function, bladder dynamics, infection history, disease severity, past surgical history, and family priorities. Its actual goal is to provide the right interventions for the right children at the right time, while avoiding unnecessary examinations to protect long-term function and quality of life [15, 16, 41].

Patient-specific factors

Effective personalized treatment requires a systematic evaluation of the patient's specific

factors. Relevant variables include anatomical structure, severity of disease, kidney function and bladder function, age and patient size, history of infection, past surgical intervention, and expected long-term consequences after treatment or observation. These factors will affect the management of diseases such as VUR and UPJO, and determine the technical feasibility and possible burden of minimally invasive reconstruction [2, 15, 23, 42].

Anatomical structure: A prominent feature of congenital urinary system diseases is the heterogeneity of the anatomical structure. There may be significant differences in the structural morphology and complexity of UPJO, VUR and hypospadias, which not only affects the choice of surgical indication, but also determines the formulation of technical strategies. Advanced imaging and patient-specific 3D models help to delineate anatomical relationships of individual patients more clearly, especially in complex reconstructive cases. Understanding the anatomy in this way is conducive to individualized surgical planning. At the same time, it should be recognized that imaging technology is a supplement to clinical and functional evaluation, not a substitute [2, 4, 13].

The severity of the disease: The severity of the disease is another key factor in the formulation of individualized treatment plans. In VUR, depending on the degree of inversion, infection history, kidney performance, bladder-intestinal dysfunction and conservative treatment response, the treatment methods may range from observational treatment to endoscopic injection or surgical re-implantation. In UPJO, symptoms, drainage, change trend of kidney function and progression of obstruction will affect whether to choose observation or surgery. By adjusting the intensity of the intervention according to the risk, it helps to reduce overtreatment and ensure that patients with clinically important obstruction or renal function risk receive timely treatment [2, 23].

Minimally invasive technologies and emerging technologies in personalized treatment

The combination of minimally invasive surgery and emerging technologies can support personalized medical care when the surgical selection matches the anatomical structure, disease severity and expected functional results.

Laparoscopy and robotic assistance technology provide pediatric patients with alternative paths that can be customized for reconstruction, which can reduce tissue damage when appropriately selected [5-7, 18].

Emerging technologies such as artificial intelligence and three-dimensional modeling can further support personalized treatment by assisting risk stratification and providing patient-specific anatomical information for complex surgical planning. Its clinical value depends on proper verification and still needs to be proven that it can improve specific decision-making or treatment results [12, 13].

Overall, information management system, artificial intelligence and patient-specific imaging technology can jointly build a more personalized diagnosis and treatment model for children's urology. The minimally invasive platform provides an alternative technical path for properly screened surgery. Artificial intelligence can be used for risk stratification after verification, while the three-dimensional model helps to clearly present complex anatomical structures to assist preoperative planning. When these technologies are combined with clear clinical decision-making and quantifiable patient benefits, their contribution to precision medicine will be more significant [12, 13, 15].

Growth monitoring, long-term follow-up and joint decision-making

Personalized children's urology treatment should not be limited to surgery itself, because congenital urinary system diseases may affect kidney growth, bladder function, urination control ability, infection risk and quality of life for many years. Therefore, long-term follow-up should be adjusted according to the risk of specific diseases. For children with stable kidney function, gradually improving obstruction and no recurrence symptoms, less follow-up may be required; while children with bilateral lesions, renal compensatory disorders, repeated febrile urinary tract infections, abnormal bladder dynamics or have failed treatment need to be monitored more closely. Long-term pyeloplasty data highlight the importance of including durable outcomes in the evaluation, not just relying on perioperative indicators [2, 3, 23].

Joint decision-making is equally important. Parents or guardians usually make major treatment decisions on behalf of young children, while older children and adolescents should participate in the decision-making process according to their developmental ability. The discussion should cover the expected success, uncertainty, anesthesia exposure, pain, scars, postoperative implants, recovery time, risks of further surgery and local surgery experience. In certain cases, robotic surgery may have advantages in terms of technology and recovery, but the existing literature does not prove the use of robotic platforms as the main indication for surgery. The most appropriate intervention is still a plan that strikes a balance between disease severity, anatomical feasibility, long-term function, treatment burden and family priorities [7]. Digital technology can assist these discussions without replacing them. 3D models for patients can improve the visualization of complex anatomical structures, and proven prediction tools may help convey the estimated risk of disease progression or treatment failure in the future [12, 13]. However, personalization does not necessarily mean higher technical intensity. For some children, the use of structured ultrasound examination and clinical follow-up for observation is more individualized than immediate intervention. The core principle is to adjust the intensity of treatment and follow-up according to biological and functional risks, while minimizing the cumulative burden of childhood.

Longitudinal outcome of kidney and bladder

The personalized strategy should also recognize that the recovery trajectory of the kidneys and bladder may be different after technically successful treatment. In UPJO, after successful ureteroplasty, drainage and hydronephrosis usually improve, but there is a difference in the speed of imaging recovery, and residual expansion does not necessarily mean recurrent obstruction. Therefore, long-term evaluation should be combined with clinical needs, comprehensive symptoms, regular ultrasound examination and kidney function detection, rather than relying only on a single postoperative imaging result. Comparative follow-up studies of open and robot-assisted pyeloplasty have confirmed that both methods have lasting success effects, which further emphasizes the

importance of functional outcomes and re-intervention rates when evaluating the value of surgical procedures [23]. For children with renal impairment, bilateral diseases or repeated obstruction, the monitoring requirements may be stricter than those of patients with simple unilateral lesions.

For VUR and PUV, the results of longitudinal follow-up are largely affected by bladder function and the risk of infection. In VUR, the persistence or remission of reflux shown by imaging is only one aspect of the prognosis; febrile urinary tract infection, kidney scar formation, bladder-intestinal dysfunction and compliance with conservative treatment may change the significance of imaging findings and the necessity of intervention [2, 11, 24, 25]. In PUV, endoscopic valve ablation can remove anatomical obstruction, but it cannot reverse the formed renal dysplasia and may not restore normal bladder function. Although the initial endoscopic results were good, some boys may still have incomplete emptying, decreased bladder conformability, urinary incontinence, repeated infection or gradual deterioration of renal function [3]. These circumstances show that the success of children's urinary system surgery should be evaluated on a multi-year standard, not just limited to judgment at the time of discharge.

In long-term studies, patient reports and family-centered treatment results should also receive more attention. Even if the routine surgery results are good, repeated imaging examinations, catheter insertion, stent removal, urinary system symptoms, absence from classes, going to tertiary medical centers and anxiety about repeated operations may still bring a greater treatment burden. Therefore, the truly personalized treatment path should maintain the ability to detect the deterioration of the disease at an early stage while reducing unnecessary follow-up visits. Risk-based follow-up plans, standardized symptom assessments, and clear further functional testing standards help to achieve this balance. Digital tools can assist in collecting longitudinal data, but should be used as a supplement to direct clinical evaluation, not as a substitute, especially when symptoms, kidney function or bladder behavior change.

The integration of minimally invasive surgery and new technology

Combining MIS with emerging technologies can create a more data-driven clinical workflow for individual patients. MIS provides an operating platform for properly selected surgical interventions, and technologies such as artificial intelligence, advanced imaging technology and three-dimensional modeling can improve the level of risk assessment and preoperative planning after clinical verification. Therefore, the value of technological integration should be judged by the quality of decision-making, security, recovery or measurable improvement in long-term prognosis, and should not be based on technical complexity as the only criterion [7, 12, 13].

Synergistic relationship to improve the effect of diagnosis and treatment

Integrating MIS with emerging technologies is expected to optimize the clinical workflow of pediatric urology through accurate surgical access, more perfect preoperative information and personalized patient plans. The robot platform can assist in complex reconstruction operations, artificial intelligence can be used to support data-based risk assessment, and the three-dimensional model can improve the visualization of preoperative anatomy. These technologies are complementary rather than interchangeable, and their respective technical evidence should be evaluated separately. Therefore, the most effective implementation model is to choose a technology, because it can solve specific clinical problems and bring measurable value to safety, planning, rehabilitation or long-term prognosis [7, 12, 13, 35].

Workflow integration: from diagnosis to follow-up

The main advantage of combining MIS with new technology is that it can support continuous clinical workflows from beginning to end. This integrated path can manifest as a continuous process, covering diagnosis, planning, surgery and postoperative follow-up.

In the integrated workflow, diagnosis and monitoring begin with high-quality clinical evaluation and imaging, and artificial intelligence is only used as a proven decision-making support tool

under appropriate circumstances. In the planning stage, the three-dimensional reconstruction based on the individual patient helps to clarify the complex anatomical structure and guide the surgical plan. During the operation, laparoscopic or robotic surgery techniques can be selected according to the reconstruction task and the professional ability of the institution. After surgery, the recovery and functional outcome can be monitored through longitudinal clinical and imaging data. With the accumulation of digital data, they may provide structured feedback for future risk models, but such systems require careful governance and forward-looking verification [7, 12, 13, 29].

Feasibility of practical application

Although MIS has many advantages in combining with new technologies, there are still some problems in the implementation of the system in actual clinical institutions. The cost of introducing complex technologies, especially robotics and 3D printing equipment, may become an obstacle to access to technology in resource-poor environments. In addition, private support, interdisciplinary cooperation and professional training are crucial to the successful implementation of these innovations.

Differences in medical institutions and professional levels in different regions will also affect the degree of promotion of such technologies. In most cases, clinicians have to find a balance between the potential of new technologies and practical factors such as cost-effectiveness and reach. However, the current trend of technological innovation and increasing emphasis on value-based medical models is expected to further improve the accessibility and scalability of technology. With more and more evidence of the clinical and economic advantages of these methods, the above comprehensive strategies will be more widely applied [19, 20].

Institutional implementation and quality assurance

For the successful implementation of advanced minimally invasive surgery, it is not enough to obtain a robot platform or new imaging software. Medical institutions need to establish a standardized process, covering patient screening, preoperative planning, team training, intraoperative emergency response and postopera-

tive follow-up. In robotic surgery, the safe use of infants and young children requires familiarity with body positioning, puncture spacing, docking operation, instrument replacement, anesthesia precautions and emergency disassembly. The current review shows that pediatric robotic surgery has gone far beyond the scope of ureteroplasty, but the surgical effect still depends on the professional level of specific surgical techniques and the operation of the preoperative and postoperative coordination system [7, 18]. Therefore, it is very important to formulate a structured learning curve strategy. Simulation, guidance or supervision, the gradual improvement of the complexity of cases, and the prospective evaluation of transformation, complications, reoperation and functional outcomes help medical institutions to distinguish the proficiency of technical platforms and the mastery of basic reconstruction surgery. Quality assurance should also include patient-centered indicators, such as analgesic use, catheter or stent-related complications, unplanned emergency visits, return to school, and recovery status reported by nursing staff. These measures are especially useful when different techniques are similar in terms of surgical success rate and the main benefit expected by MIS is to reduce the burden of the perioperative period [7, 21, 22].

Fairness and opportunity costs should also be considered when implementing decisions. Robot systems, advanced imaging technology, artificial intelligence infrastructure and 3D printing technology require a lot of capital investment and professional support. Only when these technologies can solve clear clinical problems and provide added value compared with low-cost alternatives can their application be more reasonable. Regional referral networks, centralized image segmentation, and multidisciplinary case review help small hospitals gain advanced expertise without the need to rebuild expensive infrastructure. This kind of model can promote fair access while ensuring quality and avoid excessive use caused by technology-driven [19, 20].

Challenges and limitations

Despite significant progress in MIS and emerging technologies, there are still some important limitations in pediatric urology. These

obstacles include economic restrictions, technical learning curves, uneven access to specialized infrastructure, ethical and governance issues related to artificial intelligence, and the lack of forward-looking multi-center evidence for many new applications [7, 12, 19-22, 30-32].

Cost and accessibility

Although the advanced information management system has important clinical advantages, its operation still requires a lot of resources. Robot systems involve high procurement, maintenance and operation costs, and the number of children's surgeries is usually lower than that of adults. The limited activity space of infants and young children also increases the difficulty of technical operation. These factors may limit the convenience of patients' access to high-capacity tertiary health centers and raise questions about the cost-effectiveness and equitable distribution of technology. Therefore, medical institutions should evaluate whether the advanced platform provides sufficient added value to the types and populations of surgeries they apply [7, 19, 20].

Training requirements

The successful implementation of MIS and technology-based care depends on systematic training. Surgeons must master the technical skills of laparoscopic or robotic surgery, while multidisciplinary teams need to be familiar with imaging workflow, data interpretation, anesthesia precautions, and troubleshooting and solving specific problems during the operation. Simulation training and planned exercises help maintain proficiency in laparoscopic operations, and a wider range of patient safety literature supports simulation-based systematic training. In the field of pediatric robotics, training should gradually transition from appropriately selected cases to more complex reconstructive surgery, and prospective monitoring of the conversion process, complications and functional outcomes [7, 21, 22].

Ethical issues: artificial intelligence bias and data security

The use of artificial intelligence in clinical nursing raises important ethical issues. When the algorithm is trained on the data set that cannot

fully represent its subsequent application population, bias may occur, leading to systematic differences. Large-scale clinical data has also raised concerns about privacy, informed consent, data security and secondary use. In addition, the increased autonomy of medical robots and algorithm-assisted decision-making has also raised questions about accountability and supervision. Therefore, in order to ensure secure applications, transparent model development, external verification, governance framework and continuous human responsibility must be carried out [30-32, 43].

Evidence quality, comparative validity and report

Another limitation of the literature is the uneven quality of comparative evidence. Many pediatric minimally invasive surgery studies are retrospective and come from high-flow referral centers. In these centers, the experience of surgeons, patient screening, perioperative processes and access to special equipment are different from conventional clinical practice. When a new minimally invasive technique is introduced, selection bias is particularly important, because early cases may involve older or larger children with less complex anatomy or operated by surgeons with rich laparoscopic experience. Therefore, if such studies are compared with open surgery without adjustment, it may exaggerate or cover up the differences caused by the surgical method itself. The systematic evaluation of MIS complications in children also shows that it is necessary to adopt a standardized definition and conduct adequate follow-up when evaluating safety [17].

Future comparative studies should report the patient's age and weight, diagnosis and anatomical complexity, past surgical history, relevant kidney function or bladder function, surgical method, whether to change to open surgery, complications, pain relief needs, hospitalization time, re-intervention and follow-up time. For ureteroplasty, whether it is open surgery, laparoscopy or robotic surgery, the technical success rate is high, which means that the comparison of clinical significance increasingly depends on the perioperative burden, long-term obstruction-free survival rate, renal function protection and resource use, rather than a simple binary success rate [8-10, 23]. Similarly,

the study on VUR should distinguish between reflux relief on imaging and the prevention of fever infection and kidney damage, because these outcomes are related but not interchangeable [2, 11, 24, 25]. A unified definition of outcome will help meta-analysis and enable families to compare different treatment plans based on clinically significant endpoint indicators.

Technology-focused research requires additional reporting standards. For artificial intelligence, researchers should describe the data source, sample size, processing methods for missing data, model development process, internal and external verification, calibration, subgroup performance and clinical consequences caused by errors. The high distinction in the retrospective data set does not prove that the model can improve decision-making or results in practice [12, 26, 30, 44]. In terms of three-dimensional modeling, the study should clarify the imaging acquisition method, segmentation method, model accuracy, production time, cost, and the specific decision-making or surgical steps that the model aims to improve [13, 33-35]. In the field of robotics, the report should consider the learning curve and distinguish the platform-related results from the results of foundation reconstruction surgery [5-7, 18].

Multicenter registration and prospective collaborative research are particularly important in the field of pediatric urology, because many congenital malformations and complex surgeries are rare in a single medical institution. Shared data standards can enhance statistical effectiveness, detect rare adverse events, and make the external verification of predictive models more realistic. In addition, implementation studies are needed to assess whether innovative technologies can be replicated in non-expert centers and whether their benefits are sufficient to justify the investment in additional training, infrastructure and costs. The goal should be the adoption of evidence-based guidance: technologies of clinical value should be included in the diagnosis and treatment process, while those promising but unverified tools should be kept in structured research or quality improvement projects until their safety, effectiveness and generalization are confirmed [19-22, 45].

Future development direction

In the future, pediatric urology will be more affected by the deep integration of data-driven prediction, advanced imaging technology and precise treatment planning. With the expansion of data sets and the improvement of standardization, artificial intelligence is expected to provide support in risk stratification, image interpretation and prognosis prediction, but its clinical value should be verified through prospective research, rather than relying solely on technical performance inference. Deep learning and machine learning literature in the medical field provide the basis for methodology, while the specific research on pediatric urology has begun to clarify the relevant applications and limitations [12, 26, 42, 44].

Robot platforms may also develop in a direction that is smaller, more ergonomic, more flexible and more acceptable to pediatric patients. At the same time, tissue engineering and regenerative medicine will continue to use technological advances such as biomaterials, autologous cells, scaffolds and 3D bioprinting to explore individualized alternatives for bladder and urethral reconstruction. These methods are still at different stages of maturity and still need long-term security and functional verification. Finally, it is necessary to standardize the clinical path and implement science to transform innovative results into repeatable clinical practices while avoiding unnecessary technical differences [7, 14, 18, 37-39, 43, 45].

The actual development route of precision pediatric urology should be promoted in stages. In the short term, centers should give priority to technologies with clear clinical application value and a reproducible evidence basis, and gradually introduce new tools through the forward-looking quality improvement framework. The robotic surgery project can track the specific results of the operation and regularly evaluate whether hospitalization time, rehabilitation, complications and re-intervention are sufficient to prove the reasonableness of additional resource investment. The ever-expanding literature on children's robots supports continuous innovation, but also calls for larger-scale prospective research, cost analysis and careful evaluation of the learning curve [7, 19, 20].

In the medium term, the interoperability between imaging systems, electronic medical records, predictive algorithms and surgical planning tools is expected to achieve a more continuous and personalized diagnosis and treatment process. For example, children with UPJO can integrate continuous ultrasound examination, kidney function information, symptoms and infection history into a structured risk assessment, and retain three-dimensional reconstruction in cases with complex anatomy. Artificial intelligence can be used as a second reader or a risk stratification auxiliary tool, but its clinical application should follow external verification and continuous performance monitoring [12, 13].

In the long run, the progress of regenerative medicine, molecular profiling, digital follow-up and individualized tissue engineering may further expand treatment options. However, these advances should be measured by results that are vital to children and their families: kidney function protection, urinary control, protection from infection and repeated surgery, participation in normal activities, and quality of life. Technology should always be used as a means to improve vertical care, not an independent endpoint. A multi-center registration system and a unified definition of outcome will be very important, because many congenital diseases and complex surgeries are not common in individual medical institutions [14, 37-39].

Standardization is particularly important for technologies such as 3D modeling. Consistent reporting of image acquisition, segmentation, model construction, quality assurance, production time, and the specific surgical decision influenced by the model will make studies easier to compare and reproduce. Similar principles should be applied to AI model development and robotic outcomes. By combining innovation with disciplined evidence generation, pediatric urology can move toward precision care without making treatment unnecessarily complex or inequitable [7, 12, 13].

Conclusion

In summary, the future of pediatric urology is undergoing a significant transformation driven by the convergence of new technologies and minimal invasive surgical methods. MIS has

become an established component of pediatric urological care and serves as a foundation for the integration of emerging precision technologies. They can be enhanced by the introduction of technologies, including artificial intelligence, three-dimensional modelling, and tissue engineering, which facilitate more accurate, personalized, and effective treatment. This narrative review outlines how these innovations are likely to change over the continuum of care-diagnosis and preoperative planning, surgical intervention and postoperative follow-up. The combination of these methods can be used to facilitate the shift towards personalized medicine, in which treatment plans are taken according to the specificity of the patient, such as anatomical differences, severity of an illness, and the functional outcome. However, even with such improvements, there are still a number of challenges posed which are; high cost, training needs, ethical issues and limited large-scale clinical validation. It will be imperative to tackle these obstacles in order to have equal access and long-term sustainability of these technologies in practice.

Disclosure of conflict of interest

None.

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References

- [1] Nguyen HT, Herndon CDA, Cooper C, Gatti J, Kirsch A, Kokorowski P, Lee R, Perez-Brayfield M, Metcalfe P, Yerkes E, Cendron M and Campbell JB. The Society for Fetal Urology consensus statement on the evaluation and management of antenatal hydronephrosis. *J Pediatr Urol* 2010; 6: 212-231.
- [2] Hajiyev P and Burgu B. Contemporary management of vesicoureteral reflux. *Eur Urol Focus* 2017; 3: 181-188.
- [3] Nasir AA, Ameh EA, Abdur-Rahman LO, Adeniran JO and Abraham MK. Posterior urethral valve. *World J Pediatr* 2011; 7: 205-216.
- [4] Pippi Salle JL, Sayed S, Salle A, Bagli D, Farhat W, Koyle M and Lorenzo AJ. Proximal hypospadias: a persistent challenge. Single institution outcome analysis of three surgical techniques over a 10-year period. *J Pediatr Urol* 2016; 12: 28.e1-28.e7.
- [5] Chen CJ and Peters CA. Robotic assisted surgery in pediatric urology: current status and future directions. *Front Pediatr* 2019; 7: 90.
- [6] Andolfi C, Kumar R, Boysen WR and Gundeti MS. Current status of robotic surgery in pediatric urology. *J Laparoendosc Adv Surg Tech A* 2019; 29: 159-166.
- [7] Hou SW, Xing MH and Gundeti MS. Pediatric robotic urologic procedures: indications and outcomes. *Indian J Urol* 2023; 39: 107-120.
- [8] Penn HA, Gatti JM, Hoestje SM, DeMarco RT, Snyder CL and Murphy JP. Laparoscopic versus open pyeloplasty in children: preliminary report of a prospective randomized trial. *J Urol* 2010; 184: 690-695.
- [9] Gatti JM, Amstutz SP, Bowlin PR, Stephany HA and Murphy JP. Laparoscopic versus open pyeloplasty in children: results of a randomized, prospective, controlled trial. *J Urol* 2017; 197: 792-797.
- [10] Huang Y, Wu Y, Shan W, Zeng L and Huang L. An updated meta-analysis of laparoscopic versus open pyeloplasty for ureteropelvic junction obstruction in children. *Int J Clin Exp Med* 2015; 8: 4922-4931.
- [11] Elder JS, Diaz M, Caldamone AA, Cendron M, Greenfield S, Hurwitz R, Kirsch A, Koyle MA, Pope J and Shapiro E. Endoscopic therapy for vesicoureteral reflux: a meta-analysis. I. Reflux resolution and urinary tract infection. *J Urol* 2006; 175: 716-722.
- [12] Scott Wang HH, Vasdev R and Nelson CP. Artificial intelligence in pediatric urology. *Urol Clin North Am* 2024; 51: 91-103.
- [13] Silvestro E, Kolon TF, Canning D, Serai SD, Carson R, Sze R and Back SJ. Pediatric genitourinary 3D modeling and printing using multi-phase postcontrast imaging segmentation. *Urology* 2023; 173: 149-152.
- [14] Atala A, Bauer SB, Soker S, Yoo JJ and Retik AB. Tissue-engineered autologous bladders for patients needing cystoplasty. *Lancet* 2006; 367: 1241-1246.
- [15] Jameson JL and Longo DL. Precision medicine—personalized, problematic, and promising. *N Engl J Med* 2015; 372: 2229-2234.
- [16] Ashley EA. The precision medicine initiative: a new national effort. *JAMA* 2015; 313: 2119-2120.
- [17] Aksenov LI, Granberg CF and Gargollo PC. A systematic review of complications of minimally invasive surgery in the pediatric urological literature. *J Urol* 2020; 203: 1010-1016.
- [18] Orvieto MA, Large M and Gundeti MS. Robotic paediatric urology. *BJU Int* 2012; 110: 2-13.
- [19] Childers CP and Maggard-Gibbons M. Estimation of the acquisition and operating costs for robotic surgery. *JAMA* 2018; 320: 835-836.

- [20] Barbash GI and Glied SA. New technology and health care costs—the case of robot-assisted surgery. *N Engl J Med* 2010; 363: 701-704.
- [21] Stefanidis D, Korndorffer JR Jr, Markley S, Siererra R and Scott DJ. Proficiency maintenance: impact of ongoing simulator training on laparoscopic skill retention. *J Am Coll Surg* 2006; 202: 599-603.
- [22] Aggarwal R, Mytton OT, Derbrew M, Hananel D, Heydenburg M, Issenberg B, MacAulay C, Mancini ME, Morimoto T, Soper N, Ziv A and Reznick R. Training and simulation for patient safety. *Qual Saf Health Care* 2010; 19: i34-i43.
- [23] Salö M, Sjöberg Altemani T and Anderberg M. Pyeloplasty in children: perioperative results and long-term outcomes of robotic-assisted laparoscopic surgery compared to open surgery. *Pediatr Surg Int* 2016; 32: 599-607.
- [24] Puri P, Kutasy B, Colhoun E and Hunziker M. Single center experience with endoscopic subureteral dextranomer/hyaluronic acid injection as first line treatment in 1,551 children with intermediate and high grade vesicoureteral reflux. *J Urol* 2012; 188: 1485-1489.
- [25] Routh JC, Inman BA and Reinberg Y. Dextranomer/hyaluronic acid for pediatric vesicoureteral reflux: systematic review. *Pediatrics* 2010; 125: 1010-1019.
- [26] Rajkomar A, Dean J and Kohane I. Machine learning in medicine. *N Engl J Med* 2019; 380: 1347-1358.
- [27] Hashimoto DA, Rosman G, Rus D and Meireles OR. Artificial intelligence in surgery: promises and perils. *Ann Surg* 2018; 268: 70-76.
- [28] Keays MA, Guerra LA, Mihill J, Raju G, Al-Asheeri N, Geier P, Gaboury I, Matzinger M, Pike J and Leonard MP. Reliability assessment of Society for Fetal Urology ultrasound grading system for hydronephrosis. *J Urol* 2008; 180 Suppl: 1680-1683.
- [29] Bates DW, Saria S, Ohno-Machado L, Shah A and Escobar G. Big data in health care: using analytics to identify and manage high-risk and high-cost patients. *Health Aff (Millwood)* 2014; 33: 1123-1131.
- [30] Kelly CJ, Karthikesalingam A, Suleyman M, Corrado G and King D. Key challenges for delivering clinical impact with artificial intelligence. *BMC Med* 2019; 17: 195.
- [31] Obermeyer Z, Powers B, Vogeli C and Mullainathan S. Dissecting racial bias in an algorithm used to manage the health of populations. *Science* 2019; 366: 447-453.
- [32] Price WN 2nd and Cohen IG. Privacy in the age of medical big data. *Nat Med* 2019; 25: 37-43.
- [33] Mitsouras D, Liacouras P, Imanzadeh A, Giannopoulos AA, Cai T, Kumamaru KK, George E, Wake N, Caterson EJ, Pomahac B, Ho VB, Grant GT and Rybicki FJ. Medical 3D printing for the radiologist. *Radiographics* 2015; 35: 1965-1988.
- [34] Chepelev L, Wake N, Ryan J, Althobaity W, Gupta A, Arribas E, Santiago L, Ballard DH, Wang KC, Weadock W, Ionita CN, Mitsouras D, Morris J, Matsumoto J, Christensen A, Liacouras P, Rybicki FJ and Sheikh A; RSNA Special Interest Group for 3D Printing. Radiological Society of North America (RSNA) 3D printing Special Interest Group (SIG): guidelines for medical 3D printing and appropriateness for clinical scenarios. *3D Print Med* 2018; 4: 11.
- [35] Martelli N, Serrano C, van den Brink H, Pineau J, Prognon P, Borget I and El Batti S. Advantages and disadvantages of 3-dimensional printing in surgery: a systematic review. *Surgery* 2016; 159: 1485-1500.
- [36] Atala A. Engineering tissues, organs and cells. *J Tissue Eng Regen Med* 2007; 1: 83-96.
- [37] Murphy SV and Atala A. 3D bioprinting of tissues and organs. *Nat Biotechnol* 2014; 32: 773-785.
- [38] Raya-Rivera A, Esquiliano DR, Yoo JJ, Lopez-Bayghen E, Soker S and Atala A. Tissue-engineered autologous urethras for patients who need reconstruction: an observational study. *Lancet* 2011; 377: 1175-1182.
- [39] Zhang YS, Yue K, Aleman J, Moghaddam KM, Bakht SM, Yang J, Jia W, Dell'Erba V, Assawes P, Shin SR, Dokmeci MR, Oklu R and Khademosseini A. 3D bioprinting for tissue and organ fabrication. *Ann Biomed Eng* 2017; 45: 148-163.
- [40] Hollister SJ. Porous scaffold design for tissue engineering. *Nat Mater* 2005; 4: 518-524.
- [41] Hamburg MA and Collins FS. The path to personalized medicine. *N Engl J Med* 2010; 363: 301-304.
- [42] Topol EJ. Individualized medicine from prewomb to tomb. *Cell* 2014; 157: 241-253.
- [43] Yang GZ, Cambias J, Cleary K, Daimler E, Drake J, Dupont PE, Hata N, Kazanzides P, Martel S, Patel RV, Santos VJ and Taylor RH. Medical robotics-regulatory, ethical, and legal considerations for increasing levels of autonomy. *Sci Robot* 2017; 2: eaam8638.
- [44] Esteva A, Robicquet A, Ramsundar B, Kuleshov V, DePristo M, Chou K, Cui C, Corrado G, Thrun S and Dean J. A guide to deep learning in healthcare. *Nat Med* 2019; 25: 24-29.
- [45] Pronovost PJ, Berenholtz SM and Needham DM. Translating evidence into practice: a model for large scale knowledge translation. *BMJ* 2008; 337: a1714.