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Review Article

Paediatrics Section

Artificial Intelligence in Paediatric Urology: Transforming Diagnosis and Treatment

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ABSTRACT

Artificial Intelligence (AI) is revolutionising healthcare, including paediatric urology. Paediatric urology has played a crucial role in the development of clinically relevant AI models. This narrative review explores the applications, benefits and challenges of AI in paediatric urological diagnosis and treatment. It aims to determine the current state of AI in paediatric urology, identify key applications, evaluate their impact on clinical outcomes and explore potential future directions. The literature search was extensively conducted using the PubMed, Scopus and Web of Science databases. The findings from the literature search indicate that AI has the potential to significantly improve paediatric urological care by providing more accurate diagnosis, optimising treatment decisions and enhancing surgical outcomes. However, challenges such as data quality, model generalisability and ethical implications must be resolved for widespread implementation.

Keywords: Algorithms, Deep learning, Diagnosis, Machine learning, Predictive modelling, Robotic surgery, Treatment

INTRODUCTION

AI is emerging in various streams of health sciences, including paediatric urology. It is providing valuable solutions to long-standing clinical challenges. Paediatric urology encompasses a wide range of minimally invasive surgical procedures designed to manage a diverse array of urological conditions affecting children [1]. Children frequently present with complex urological diseases that require customised modalities for precise identification. The incorporation of AI into paediatric urology has marked the beginning of a new era of precision medicine, where AI-powered prediction models have shown promising results in enhancing diagnostic accuracy, advancing surgical techniques and developing customised therapeutic strategies. This growing field is anticipated to revolutionise the approach of clinicians and researchers in managing critical urological conditions in the paediatric population. AI can significantly improve the precision of diagnosis, optimise surgical methods and customise treatment plans for paediatric patients [2].

This review article delves into the burgeoning applications of AI in paediatric urology, exploring its impact on various aspects of clinical practice. The accurate diagnosis of urological anomalies in children presents unique challenges compared to adults. Traditional methods, such as Voiding Cystourethrogram (VCUG) and ultrasound imaging, exhibit limitations in terms of precision and reproducibility [3]. VCUG involves the fluoroscopic examination of the bladder and urinary tract after contrast has been instilled [4]. However, this procedure can be stressful, thus enhancing anxiety among young patients due to the subjective interpretation of VCUG images. Ultrasound imaging, while non invasive and radiation-free, may not always provide a definitive diagnosis, particularly in cases involving subtle abnormalities [5]. The specific challenges associated with providing treatment to young patients make the use of AI in paediatric urology even more critical.

By applying Machine Learning (ML) and Deep Learning (DL) algorithms, AI is revolutionising the diagnostic landscape in paediatric urology. ML algorithms, particularly supervised learning approaches, are being employed to tackle complex challenges such as predicting the severity of Vesicoureteral Reflux (VUR) [6]. ML approaches use complex non linear mathematical models to elucidate variable interactions. The most common models harnessing ML generally fall into one of the following three categories: decision trees, Support Vector Machines (SVMs), or DL (neural networks) [7]. VUR, a condition characterised by the backflow of urine from the bladder to the ureters, can potentially lead to kidney damage if left untreated. These AI models, trained on vast datasets of patient demographics, reflux grades and bladder capacity, can predict the resolution of VUR with high accuracy [8]. Thus, based on the predicted severity, clinicians can tailour treatment plans, potentially reducing unnecessary interventions and improving patient outcomes.

DL, a subfield of AI particularly adapt at image analysis, offers significant advancements in the interpretation of VCUG images. Convolutional Neural Networks (CNNs) are being applied to automate the grading of VUR severity. Studies have demonstrated that CNN models achieve accuracy comparable to, or even exceeding, that of traditional methods [9-11]. By analysing features such as reflux patterns, bladder contours and ureteral dilatation, CNNs provide objective and potentially more consistent grading, thereby streamlining the diagnostic process and reducing subjectivity.

Hydronephrosis, a condition characterised by swollen kidneys owing to fluid buildup, is another prevalent concern in paediatric urology. ML models are being developed to leverage ultrasound images for assessing the severity of hydronephrosis and identifying the underlying cause. These models assess parameters such as renal pelvis dilation and parenchymal thickness to predict the degree of obstruction, thus guiding subsequent treatment decisions [12].

Furthermore, AI algorithms demonstrate promising outcomes in predicting the necessity for surgical intervention in cases of hydronephrosis. By analysing preoperative ultrasound data, including stone size, location and patient history, these algorithms can estimate the likelihood of spontaneous resolution versus the need for surgical procedures, like pyeloplasty. This information empowers clinicians to engage in shared decision-making with families, fostering a more patient-centred approach [13].

The primary aim of this narrative review is to comprehensively analyse the current applications of AI in paediatric urology, highlighting the advancements, challenges and prospects in this rapidly evolving field. The specific objectives of this review are:

1. **To investigate the current uses of AI in paediatric urology:** This involves examining how paediatric urological problems can be diagnosed and treated through the use of robotic-assisted surgical systems, DL models and ML techniques.

2. **To evaluate the effectiveness of AI technologies in improving diagnostic accuracy:** The review will assess how AI has enhanced the precision and reliability of diagnostic tools, particularly in imaging modalities and predictive models used in paediatric urology.
3. **To identify the challenges and limitations associated with the implementation of AI in paediatric urology:** This objective aims to discuss the barriers to the widespread adoption of AI technologies, including issues related to data availability, model generalisability and ethical considerations.
4. **To assess the potential future directions for AI in paediatric urology:** The review will explore emerging trends and innovations in AI that may shape the future of paediatric urology, offering insights into the foreseeable advancements and their implications for clinical practice.
5. **To provide recommendations for integrating AI into routine clinical practice in paediatric urology:** Based on the findings, the review will suggest strategies for optimising the use of AI in clinical settings, ensuring its benefits are maximised while addressing potential risks and challenges.

Literature Search Strategy

A thorough search of the literature was conducted utilising several scholarly sources, such as IEEE Xplore, Web of Science, Google Scholar, PubMed and Scopus. Combinations of terms like "artificial intelligence," "AI," "machine learning," "deep learning," "urology," "diagnostic imaging," "robotic surgery," and "predictive modelling" were among the keywords used in the search. MeSH phrases and free-text keywords were employed to capture diverse articles and Boolean operators (AND, OR) were utilised to filter the search results.

Overview of AI Applications in Paediatric Urology: This section delves into the various AI applications, highlighting their impact on clinical practice.

Diagnostic enhancements: [Table/Fig-1] illustrates different types of AI applications in diagnostic enhancements in paediatric urology [8,14-16].

Condition	AI application	Outcomes	Study
Vesicoureteral Reflux (VUR)	Predictive modelling and AI algorithms	High accuracy in predicting VUR severity and outcomes	Kabir S et al., (2023) [8]
	Machine learning models for VUR prediction	Automated grading of VUR with accuracy exceeding traditional methods	Ergün O et al., (2024) [14]
	Deep learning for image analysis	Automated assessment of hydronephrosis severity using ultrasound images	Lien WC et al., (2023) [15]
Hydronephrosis	AI in ultrasound analysis	AI models predict obstruction severity guiding treatment decisions	Lien WC et al., (2023) [15]
	Outcome forecasting	Predicts necessity of surgical intervention based on preoperative data	Anastasiadis A et al., (2023) [16]

[Table/Fig-1]: AI applications in diagnostic enhancements for paediatric urology [8,14-16].

a) **Vesicoureteral Reflux (VUR):** AI-driven predictive models have revolutionised the diagnosis and management of VUR. Traditional diagnostic modalities, such as VCUG and ultrasound, have exhibited variability in accuracy and reproducibility [6]. ML models, including supervised learning algorithms, have been developed to predict VUR severity and therapeutic outcomes. Kabir S et al., demonstrated that VUR could be predicted with high accuracy by an ML model using patient demographics, reflux grades, and bladder capacity [8].

   CNNs have been applied to VCUG images to automate the grading of VUR. These CNNs analyse features such as reflux patterns, bladder contours, and ureteral dilatation to provide objective grading [14]. A multi-head CNN for automatic VUR grading from VCUG images has been developed. This model offers greater computational efficiency, an increased ability to capture complex data relationships, and the advantage of deep supervision, thereby assisting in more consistent and robust feature learning [17].

b) **Hydronephrosis:** The severity of hydronephrosis was determined using AI models developed by Lien WC et al., which analyse ultrasound images. These models assess parameters such as renal pelvis dilation and parenchymal thickness to predict the severity of obstruction, thereby guiding subsequent treatment decisions [15]. Additionally, Anastasiadis A et al., developed AI algorithms that predict the necessity of surgical intervention for hydronephrosis based on preoperative ultrasound data. The algorithms integrate variables such as stone size, stone location and patient history to estimate the likelihood of spontaneous resolution versus the need for surgical intervention [16].

c) **Robotic-Assisted Laparoscopic Surgery (RALS):** RALS has become an essential tool in paediatric urology, offering enhanced precision and reduced invasiveness compared to traditional methods [Table/Fig-2]. RALS is employed for complex paediatric urological procedures, including pyeloplasty, partial nephrectomy and ureteral reimplantation. Hou SW et al., reviewed multiple studies demonstrating that RALS provides increased dexterity, improved visualisation and reduced postoperative pain compared to conventional laparoscopic surgery [18].

Procedure	AI application	Clinical outcomes	Study
Pyeloplasty, partial nephrectomy, ureteral reimplantation	RALS for complex procedures	Increased dexterity, improved visualisation, reduced pain	Hou SW et al., (2023) [18]
Outpatient surgery	Feasibility of outpatient RALS	Safe and effective with low complication rates	Broch A et al., (2023) [20]
Technical considerations	Advancements in robotic technology and training	Improved safety profile and expanded RALS applications	Hou SW et al., (2023) [18]

[Table/Fig-2]: Robotic-Assisted Laparoscopic Surgery (RALS) in paediatric urology [18,20].

   In the paediatric population, Silay MS et al., conducted the first Randomised Controlled Trial (RCT) comparing Laparoscopic Procedure (LP) with Robotic-Assisted Laparoscopic Prostatectomy (RALP). Both LP and RALP proved to be safe and effective for children, with similar success and complication rates. While RALP's overall cost was greater, LP's operating duration was longer [19].

   Recent investigations into RALS focus on safety and feasibility, particularly for outpatient procedures. Broch A et al., explored the feasibility of performing retroperitoneal robotic-assisted laparoscopic pyeloplasty as an outpatient procedure. Their study demonstrated that this approach is both safe and effective, with low complication rates and potential reductions in hospital stay durations [20]. The implementation of RALS requires specialised equipment and expertise. Hou SW et al., discussed advancements in robotic technology and training programmes, which have improved the safety profile and expanded the applications of RALS in paediatric urology [18].

d) **Renal stones:** AI technologies have advanced the management of paediatric kidney stones by optimising treatment strategies. AI models have been developed to predict the outcomes of therapies like Percutaneous Nephrolithotomy (PCNL) and Extracorporeal Shock Wave Lithotripsy (ESWL). Tzelves L et al., focus on advancements in kidney stone removal, which include new lasers, contemporary ureteroscopes, applications, and training systems developed using three-dimensional models, virtual reality, AI, robotic system implementation, sheaths attached to vacuum devices, and novel lithotripters. These advancements in kidney stone removal have ushered in a new and exciting era of endourological alternatives for both patients and professionals alike [21].

e) **Bladder augmentation and reconstruction:** The AI applications in bladder augmentation and reconstruction focus on enhancing surgical planning and predicting outcomes. AI models predict the success of bladder augmentation procedures by analysing preoperative data and surgical outcomes. Ross JPJ et al., developed models that integrate data from various sources, such as preoperative assessments and surgical histories, to forecast postoperative bladder function and potential complications [22].

AI-driven approaches facilitate personalised treatment planning by incorporating patient-specific data. These models help tailor surgical strategies to individual needs, thereby improving patient outcomes and satisfaction [Table/Fig-3] [23].

Intervention	AI application	Outcomes	Study
Renal stones	Predictive algorithms for treatment success	Enhanced prediction of ESWL and PCNL success	Tzelves L et al., (2023) [21]
Bladder augmentation and reconstruction	Outcome prediction and personalised planning	Improved prediction of postoperative outcomes and personalised surgical strategies	Ross JPJ et al., (2020) [22]

[Table/Fig-3]: AI-driven innovations in urological interventions [21,22].

f) **Detrusor Overactivity (DO):** Detrusor Overactivity (DO), characterised by involuntary bladder muscle contraction, includes variable symptoms such as urgency, incontinence and frequency [24]. Noticeable efficacy has been exhibited by ML algorithms in detecting DO patterns in Urodynamic Studies (UDS), which can enable consistent interpretation and increase the precision of diagnosis [25]. Advanced imaging techniques, such as Contrast-Enhanced Ultrasound (CEUS), are radiation-free and extremely sensitive diagnostic methods. The diagnosis of DO in paediatric patients has historically been challenging due to the inconsistent interpretation of Urodynamic Tests (UDTs). Hobbs KT et al., overcame this challenge by creating an ML system called the Paediatric Detrusor Overactivity Identification system (PDOIA), designed exclusively for paediatric patients with spina bifida [26]. ML methods, like the Detrusor Under Activity Management Algorithm (DUMA), demonstrate the potential to enhance treatment choices and outcomes for patients with Detrusor Underactivity (DUA) [27].

g) **Posterior Urethral Valve (PUV):** PUV is a congenital defect characterised by obstructive tissue folds within the male urethra, which manifest as a range of urinary tract symptoms in newborns and infants. Weaver JK et al., emphasised the application of DL to extract characteristics from postnatal kidney ultrasounds that forecast progression to Chronic Kidney Disease (CKD) in children with PUV [28].

Challenges and Future Directions

AI models in paediatric urology face challenges related to generalisability and reproducibility across different clinical settings. Ensuring the reliability of AI models across diverse populations and healthcare environments is essential. Youssef A et al., emphasised the need for robust external validation to confirm AI model performance in various clinical contexts [29].

The development of standardised protocols for AI research is crucial for ensuring comparability and integration. Chang TC et al., advocated for universal standards in AI applications to enhance reliability and facilitate broader adoption [30]. In paediatric urology, ML could significantly impact patient care if it is appropriately carried out and documented. Although AI is intriguing, our ability to apply models to real-world situations is limited by the lack of compelling data. Adequate reporting and ensuring high-quality models are the initial steps toward achieving this aim [31].

Economic and Implementation Considerations

The implementation of AI technologies involves significant economic and infrastructural considerations. The costs associated with AI technologies and data infrastructure can be substantial. Wolff J et al., discussed the economic implications of AI in healthcare and highlighted the need for cost-effective solutions to promote wider adoption [32].

Infrastructure requirements: Successful AI implementation requires robust data infrastructure and integration with existing clinical workflows. Addressing these logistical challenges is crucial for the effective integration of AI technology into routine practice [32].

The integration of AI into paediatric urology has marked a significant shift in both diagnostic and therapeutic paradigms, offering new possibilities that were previously unattainable through conventional methods. This narrative review highlights the transformative potential of AI in paediatric urology, particularly in enhancing diagnostic precision, optimising surgical interventions and personalising patient care. The findings from present study align with, yet also extend, the existing literature by demonstrating how AI-driven technologies can bridge gaps in current clinical practices while introducing new challenges that require careful consideration.

AI's impact on the diagnosis of VUR is particularly noteworthy. Traditional diagnostic approaches, such as VCUG, have long been the standard; however, their variability in accuracy has led to inconsistent patient outcomes. The application of ML models, as illustrated in present review, has shown promise in improving the prediction of VUR severity and treatment outcomes. Present review findings suggest that the integration of DL algorithms, such as CNNs, can further enhance diagnostic accuracy by automating the grading of VUR. Ergün O et al., supported this assertion by showing that CNNs could classify VUR severity with precision comparable to traditional methods. This comparison underscores the potential of AI to reduce human error and increase consistency in diagnosing complex urological conditions [14].

In the context of hydronephrosis, AI's role in ultrasound image analysis represents a significant advancement. Traditional ultrasound assessments are often limited by operator dependence and subjective interpretation, leading to potential misdiagnosis or delayed treatment. Present review highlights the success of AI models in overcoming these limitations by providing objective and reproducible evaluations of hydronephrosis severity. The study by Lien WC et al., supports present review findings, demonstrating that AI models can accurately assess renal pelvis dilation and predict the need for surgical intervention [16]. This improvement in diagnostic precision enhances patient outcomes and aligns with the work of Hassan AM et al., who found that AI algorithms could effectively predict the necessity of surgical intervention based on preoperative ultrasound data. Collectively, these findings suggest that AI can serve as a valuable adjunct to traditional diagnostic tools, offering a more reliable and objective means of assessing paediatric urological conditions [33].

The advent of RALS in paediatric urology has revolutionised surgical practices by offering enhanced precision and reduced invasiveness. Present review highlights the growing role of AI in optimising these procedures, particularly in complex cases such as pyeloplasty, partial nephrectomy and ureteral reimplantation. This finding was consistent with the findings of Hou SW et al., who reviewed multiple studies demonstrating that RALS provides increased dexterity, improved visualisation and reduced postoperative pain compared to conventional laparoscopic surgery [18].

However, present study extends these findings by exploring the feasibility of RALS in outpatient settings. Knudsen JE et al., emphasised the potential of RALS to reduce hospital stay durations while maintaining safety and efficacy, a finding corroborated by present review. These advancements suggest that AI-integrated robotic systems may not only enhance surgical precision but also improve patient recovery and reduce healthcare costs [34].

While the benefits of RALS are evident, present study also highlights the challenges associated with its implementation, particularly in terms of technical considerations and economic impact. The requirement for specialised equipment and expertise, as discussed by Hou SW et al., presents a barrier to widespread adoption [18]. Furthermore, the high costs associated with AI-driven technologies, as noted by Wolff J et al., underscore the need for cost-effective solutions to facilitate broader implementation [32]. These challenges are echoed in the literature, with Silay MS et al., emphasising the need for economic feasibility in adopting new surgical technologies. The comparison between present findings and existing literature suggests that while AI has the potential to transform surgical practices in paediatric urology, addressing the logistical and economic challenges will be critical to realising its full potential [19].

Another important area of advancement in AI is its application in the treatment of juvenile kidney stones. Predictive AI models that maximise treatment success have improved conventional treatment approaches, including PCNL and ESWL. Present results are consistent with those of Tzelves L et al., who emphasised advancements in kidney stone removal, such as the application of AI-driven predictive algorithms. These developments imply that AI can be extremely important in enabling doctors to customise treatment regimens for each patient, which will enhance patient outcomes and lower the likelihood of complications [21].

In the realm of bladder augmentation and reconstruction, present review highlights the potential of AI to enhance surgical planning and outcome prediction. The use of AI models to analyse preoperative data and predict postoperative outcomes represents a significant shift from traditional methods, which often rely on surgeon experience and intuition. Ross JPJ et al., supported present review findings, demonstrating that AI-driven approaches could facilitate personalised treatment planning and improve patient satisfaction [22].

However, present review also emphasises the need for further research to validate these models across diverse patient populations and clinical settings, a concern discussed by Youssef A et al., and Chang TC et al., [29,30]. This comparison underscores the importance of standardisation and external validation in ensuring the reliability and generalisability of AI models in paediatric urology. Current models have demonstrated significant potential in paediatric urology, particularly in VUR, hydronephrosis and lower urinary tract dysfunction. A review by Ikeda A and Nosato H, of AI applications in cystoscopy and the transurethral resection of bladder tumours demonstrated that AI performance surpassed that of urologists in diagnosing lesions as benign or malignant [35].

AI integration in paediatric urology is promising for enhancing predictive accuracy and clinical care. Present review suggests that addressing these economic and logistical challenges will be critical in promoting the broader implementation of AI technologies in clinical practice. The comparison between present review findings and existing literature underscores the importance of developing cost-effective solutions that balance the benefits of AI with the financial realities of healthcare systems.

A living scoping review was conducted, and an online repository (www.aipeduro.com) was created for models to facilitate an evidence synthesis of AI models in paediatric urology [36]. Notable developments include ML and DL approaches for VUR grading, explainable models that predict obstructive hydronephrosis from ultrasound images alone, and ensemble models that integrate video urodynamic pressure tracings with fluoroscopic images to characterise bladder dysfunction [37].

CONCLUSION(S)

The integration of AI into paediatric urology represents a transformative shift in both diagnostic and therapeutic practices. Present review highlights the significant advancements made possible by AI, including enhanced diagnostic precision, optimised surgical interventions and personalised patient care. However, the successful implementation of AI in clinical practice will require addressing challenges related to generalisability, standardisation and economic feasibility.

By building on the existing literature and addressing these challenges, AI has the potential to significantly improve patient outcomes in paediatric urology and shape the future of the field. The present narrative review focuses on an in-depth analysis of the role of AI in paediatric urology, addressing the urgent need for synthesised knowledge that can guide future research, clinical practice and policy-making. Understanding the current landscape and future potential of AI in this specialised area will help clinicians, researchers and healthcare policymakers harness these technologies effectively, ensuring that the benefits of AI are fully realised while mitigating associated risks.

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