https://nephropathol.com DOI: 10.34172/jnp.2026.27689 J Nephropathol. 2026;15(3):e27689

Journal of Nephropathology

Harnessing artificial intelligence in kidney disease; current applications and future prospects

Haideh Mosleh[1], Farzaneh Futuhi[2], Sahar Kavand[3*]

[1]Department of Otorhinolaryngology, School of Medicine, Loghman Hakim Hospital, Shahid Beheshti University of Medical Sciences, Tehran, Iran

[2]Department of Adult Nephrology, School of Medicine, Loghman Hakim Hospital, Shahid Beheshti University of Medical Sciences, Tehran, Iran

[3]Department of Sports Medicine, School of Medicine, Loghman Hakim Hospital, Shahid Beheshti University of Medical Sciences, Tehran, Iran

Review

ARTICLE INFO

Article type:
Review

Article history:
Received: 20 Sep. 2025
Revised: 21 Nov. 2025
Accepted: 2 Feb. 2026
Published online: 17 Feb. 2026

Keywords:
Artificial intelligence
Machine learning
Kidney disease
Chronic kidney disease
Kidney transplantation
Dialysis

ABSTRACT

Artificial intelligence (AI) is rapidly transforming the field of nephrology by enhancing the diagnosis, prognosis, and management of kidney diseases through advanced data-driven techniques. AI-driven medical image analysis using deep learning and radiomics enables early detection of structural abnormalities in chronic kidney disease (CKD) and diabetic kidney disease (DKD), improving diagnostic accuracy and enabling standardized interpretation of ultrasound, computed tomography (CT), and magnetic resonance imaging (MRI). Machine learning (ML)models that integrate clinical, laboratory, and genetic data surpass traditional risk equations in predicting CKD progression, dialysis initiation, and mortality, facilitating personalized monitoring and intervention. In renal pathology, AI-powered digital pathology tools automate lesion detection, quantification, and classification from biopsy specimens, offering objective metrics that correlate with clinical outcomes. Within kidney transplantation, AI refines donor–recipient matching, predicts acute rejection and graft survival, and augments biopsy interpretation to optimize use of scarce donor organs. AI-enabled decision support systems and real-time monitoring algorithms in dialysis and continuous kidney replacement therapy personalize treatment parameters, enhance symptom control, and predict complications. Despite these advances, challenges related to data bias, model interpretability, ethical considerations, and clinical integration must be addressed. Prospects include the integration of multi-omics data, federated learning to protect patient privacy, explainable AI models for transparent decision-making, and telemedicine applications to extend nephrology expertise globally. Continued interdisciplinary collaboration and rigorous clinical validation will be essential to fully harness AI's potential and usher in an era of precision nephrology.

Implication for health policy/practice/research/medical education:

Artificial intelligence is revolutionizing nephrology by applying deep learning (DL) and radiomics for early, standardized detection of kidney abnormalities on ultrasound, computed tomography (CT), and magnetic resonance imaging (MRI); employing machine learning models that blend clinical, laboratory, and genetic data to more accurately predict chronic kidney disease (CKD) progression, dialysis need, and mortality; automating digital pathology of biopsies to deliver objective lesion quantification linked to outcomes; optimizing donor–recipient matching and graft survival predictions in transplantation; and guiding personalized dialysis and continuous replacement therapy through real-time decision support. While data bias, interpretability, ethics, and integration remain hurdles, future directions, such as multi-omics integration, federated learning, explainable AI, and telemedicine, promise to extend precision nephrology globally, contingent on continued interdisciplinary collaboration and rigorous clinical validation.

Please cite this paper as: Mosleh H, Futuhi F, Kavand S. Harnessing artificial intelligence in kidney disease; current applications and future prospects. J Nephropathol. 2026;15(3):e27689. DOI: 10.34172/jnp.2026.27689.

**Corresponding author:* Sahar Kavand,
Email: s.kavand@sbmu.ac.ir

Introduction

Chronic kidney disease (CKD) poses a growing global health challenge with a rising prevalence that threatens to become one of the leading causes of death worldwide by 2040 (1). Early diagnosis, timely intervention, and precise management of kidney diseases are critical to improving patient outcomes and reducing the burden of progression to end-stage kidney disease (ESKD) (2). Traditional clinical approaches, while valuable, face limitations in handling the complexity and heterogeneity inherent in renal pathophysiology (3). The advent of artificial intelligence (AI) and machine learning (ML) offers transformative potential in nephrology by enabling analysis of large-scale clinical, imaging, pathology, and molecular data (4). This narrative review summarizes the current landscape of AI applications in kidney disease, focusing on key areas such as diagnostic imaging, prognosis prediction, DKD, renal pathology, kidney transplantation, and dialysis. It further explores challenges, including data bias and algorithm interpretability, and envisions future directions to fully harness AI for personalized kidney care.

Search Strategy

A comprehensive literature search was conducted in valid databases, such as PubMed, Scopus, Web of Science, and Google Scholar search engine, to identify relevant studies on the application of AI in kidney disease published up to October 2025. The search combined keywords and Medical Subject Headings (MeSH), including "artificial intelligence," "machine learning," "deep learning," "kidney disease," "chronic kidney disease," "diabetic kidney disease," "renal pathology," "kidney transplantation," and "dialysis." Boolean operators such as AND/OR were used to refine the search and include relevant AI methodologies applied specifically to nephrology. To ensure comprehensiveness, references of key papers were also screened for additional relevant literature.

AI methodologies in medical sciences

The AI methodologies in medical sciences encompass a diverse array of computational techniques designed to analyze complex biomedical data and support clinical decision-making. Supervised learning algorithms, such as support vector machines and random forests, have been widely applied to classification tasks, including disease diagnosis and prognosis by learning from labeled datasets of clinical and imaging parameters (5). Unsupervised learning approaches, including clustering and dimensionality reduction methods like k-means and principal component analysis, facilitate the discovery of latent patient subgroups and novel biomarkers without predefined labels (6,7). Deep learning (DL) models, particularly convolutional neural networks and recurrent neural networks, excel at processing high-dimensional imaging data (e.g., radiology, pathology slides) and sequential records (e.g., electrocardiograms, electronic health record time series), achieving expert-level performance in detection and segmentation tasks (5,8). Natural language processing techniques leverage transformer-based architectures to extract meaningful information from unstructured clinical notes, enabling automated phenotyping and adverse event monitoring. Reinforcement learning frameworks are increasingly explored for optimizing treatment strategies by modeling clinical workflows as sequential decision processes (9). AI in medical sciences encompasses supervised ML algorithms (e.g., logistic regression, random forests, gradient boosting, support vector machines), DL architectures (e.g., convolutional neural networks), and hybrid approaches integrating heterogeneous data. Explainable AI techniques, such as partial dependence plots, are increasingly employed to interpret model predictions and facilitate clinician trust (10). Collectively, these AI methodologies are transforming medical sciences by enabling precision diagnostics, personalized therapeutics, and efficient healthcare delivery.

Predicting CKD progression with AI and ML

Accurate prediction of CKD progression is vital for timely therapeutic decisions and resource planning. Traditional risk models have been limited in predictive power due to reliance on linear assumptions and fewer variables. AI and ML models can integrate diverse data types, including demographics, laboratory results, comorbidities, and genetic information, to enhance predictive accuracy (11,12). Systematic reviews of ML applications in CKD prognosis report successful use of algorithms such as random forests, support vector machines, and neural networks to predict adverse outcomes like decline in glomerular filtration rate (GFR), dialysis initiation, and mortality (12). For instance, meta-analyses demonstrate that AI models outperform conventional statistical methods in forecasting CKD progression, early identification of rapid progressors, and risk stratification. Such models facilitate personalized monitoring and intervention strategies aligned with individual patient risk profiles (11).

AI in diabetic kidney disease management

Diabetic kidney disease, a leading cause of CKD, benefits significantly from AI applications for early detection and disease monitoring. AI models leveraging electronic health records (EHRs), laboratory parameters, and imaging data have been developed to identify subtle signs of DKD before overt clinical manifestations arise. ML algorithms can discern patterns in glycemic control, blood pressure, and albuminuria trends predictive of DKD onset and progression (13). Furthermore, AI aids in quantifying histopathological changes typical of DKD from biopsy images via digital pathology and DL frameworks. This is critical given the shortage of trained renal pathologists and the need for standardized diagnostic assessments. Predictive models driven by AI thus hold promise for stratifying DKD patients for targeted therapies and preventing irreversible renal damage (14).

AI in acute kidney injury prediction

Real-time prediction of acute kidney injury (AKI) in hospitalized patients enables prompt nephrology consultation and preventive measures. Contemporary AI-enabled decision support systems analyze continuous vital signs, laboratory trends, and fluid balance data to identify early AKI signals before biochemical thresholds are crossed (15,16). One study reported that ML models predicted AKI onset up to 48 hours in advance with sensitivities above 80% and specificities above 75% in intensive care settings (16).

The AI in kidney transplantation

Kidney transplantation remains the optimal therapy for ESKD, but organ shortage and graft failure demand better risk prediction and personalized management. AI models have been utilized to refine donor-recipient matching by analyzing complex donor risk factors and immunologic profiles, surpassing traditional Kidney Donor Risk Index (KDRI) limitations. ML enhances the prediction of acute rejection episodes, graft survival, and post-transplant complications through continuous monitoring of clinical and laboratory parameters (17,18). Moreover, AI-driven precision diagnostics help pathologists interpret transplant biopsy specimens with higher accuracy and reproducibility. These advances collectively improve transplant outcomes and optimize the use of scarce donor organs (17).

Advances in kidney stone management by AI

Recent advances in AI have enhanced kidney stone management through improved detection, composition analysis, and outcome prediction. Transfer learning–based DL models have demonstrated rapid and accurate detection of urinary tract stones on radiographs, facilitating early diagnosis and reducing clinician workload (19-23). AI-driven analysis of unenhanced CT radiomic features enables preoperative prediction of calcium oxalate monohydrate stones with an area under the curve (AUC) up to 0.936, guiding personalized surgical and medical strategies (23). ML classifiers trained on perioperative and imaging data accurately forecast stone-free rates and postoperative complications after ureteroscopic lithotripsy, improving patient counseling and risk stratification (22). Multimethod algorithms that integrate image processing with AI models achieve high sensitivity and specificity in stone detection, underscoring the potential for real-time clinical decision support systems in urolithiasis management (21). These collective advances highlight AI as a transformative tool in the comprehensive management of urolithiasis.

Kidney cancer management via AI

Recent advances in AI have substantially improved the detection, classification, and prognostication of kidney cancer. AI-driven segmentation techniques, such as 3D DL models, enable precise volumetric delineation of renal tumors on CT imaging, enhancing diagnostic accuracy and workflow efficiency (24). Deep convolutional neural networks applied to histopathology enable multi-class classification of renal neoplasms, distinguishing malignant subtypes from benign lesions with improved reproducibility and diagnostic confidence (25). Integration of AI in digital pathology facilitates quantitative analysis of molecular markers, fostering standardized diagnostics and prognostic assessments (26). Moreover, AI-based radiomics approaches applied to imaging facilitate early detection of renal masses at the subcentimeter scale and contribute to risk stratification, potentially guiding personalized therapeutic decisions (27). Multimodal DL frameworks combining imaging, histologic, and genomic data outperform traditional prognostic models in clear cell renal cell carcinoma, representing a promising direction for individualized patient management (28). These developments collectively mark a transformative shift in kidney cancer care through AI-enhanced precision diagnostics and prognostics

AI-enabled decision support in dialysis and continuous kidney replacement therapy

Dialysis patients experience variable symptom burden and outcomes, necessitating individualized care plans. AI-enabled decision support systems analyze EHR data, wearables, and imaging to identify symptom patterns, optimize vascular access management, and predict complications. Natural language processing (NLP) tools outperform administrative coding in capturing symptoms from clinical notes, facilitating better symptom control (29). Continuous kidney replacement therapy (CKRT) benefits from AI through real-time monitoring algorithms that adapt therapy parameters to physiological changes in critically ill patients, improving treatment efficiency and reducing adverse events. These intelligent systems promise to transform dialysis care from reactive protocols to proactive, precision strategies (30).

AI-assisted medical imaging in kidney disease

Medical imaging plays a pivotal role in detecting and monitoring kidney disease. AI techniques, especially DL and radiomics, have facilitated enhanced image analysis by extracting complex features not readily visible to human observers. For example, convolutional neural networks (CNNs) have been applied to ultrasound, computed tomography (CT), and magnetic resonance imaging (MRI) to identify early structural abnormalities, quantify kidney size, and assess fibrosis and cystic changes in CKD patients (1). Radiomics-based AI approaches have been employed successfully in autosomal dominant polycystic kidney disease (ADPKD) to predict disease progression by analyzing image texture and volumetric data. Moreover, AI-driven detection of renal tumors from imaging studies has matched or exceeded human accuracy, enabling earlier intervention. These advances highlight the potential of AI to augment radiologic expertise, streamline diagnostics, and standardize image interpretation across centers (1,31).

Advances in renal pathology through AI

Renal pathology interpretation, traditionally reliant on expert visual assessment of biopsy slides, faces challenges from workload constraints and subjective variability. AI-powered digital pathology tools use DL methods to automate the detection, segmentation, and classification of glomerular and interstitial lesions. These algorithms can quantify fibrosis, glomerulosclerosis, and inflammatory infiltrates, providing objective metrics that correlate with clinical outcomes (14). AI also offers the ability to analyze multiplex immunofluorescence and omics data alongside histology, uncovering novel biomarkers and pathways associated with kidney diseases. Integration of multi-modal data through AI frameworks accelerates discovery and precision diagnostics, enabling nephrologists to move beyond descriptive pathology toward mechanistic insights (3).

Advances in kidney laboratory tests by AI

Recent advances in AI have significantly enhanced the capabilities of kidney laboratory tests by improving diagnostic accuracy, prognostic assessment, and early detection of kidney dysfunction. AI algorithms, especially ML models, have been developed to analyze complex biochemical and clinical datasets, enabling precise prediction of CKD progression and AKI onset. These models integrate traditional laboratory markers such as estimated glomerular filtration rate (eGFR), serum creatinine, albuminuria, and electrolyte levels with additional patient data to identify subtle trends and risk patterns that surpass conventional statistical methods (32). Moreover, DL applications are enabling automated interpretation and quality control of laboratory results, reducing human error. AI-assisted platforms also facilitate dynamic monitoring of biomarkers, providing real-time risk stratification that supports personalized management planning in nephrology (18). Innovations include integrating multi-omics data with laboratory tests to decode molecular signatures associated with kidney injury and repair, as well as embedding AI models within electronic health records to trigger early alerts for nephrologists (32). Overall, AI-driven advancements in kidney laboratory testing have laid the groundwork for more proactive, precise, and personalized nephrology care, heralding a new era of data-driven diagnostics and therapeutics.

Prospects and research directions

The future of AI in kidney disease is multi-faceted and promising. Integration of multi-omics data, including genomics, proteomics, and metabolomics, with clinical and imaging datasets via AI will enable precision nephrology with individualized therapeutic targets. Federated learning frameworks that allow multi-center collaboration without sharing raw data may overcome privacy hurdles and enhance model robustness (3,18). Explainable AI models that provide transparent reasoning for predictions will foster clinician trust and facilitate shared decision-making. Furthermore, AI-driven telemedicine and remote monitoring solutions can extend nephrology expertise to underserved regions, improving access and early intervention (18,33). Continued validation of AI algorithms through prospective clinical trials and cost-benefit analyses will be vital for regulatory approval and adoption. Ultimately, leveraging AI's full potential requires interdisciplinary collaboration among nephrologists, data scientists, engineers, and ethicists (34).

Ethical, regulatory, and implementation challenges

Widespread adoption of AI in medicine faces challenges, including data quality, algorithmic bias, interoperability of health data systems, and clinician acceptance. Rigorous prospective validation, adherence to explainability standards, and robust data governance frameworks are critical to ensure patient safety and equitable care (10). Despite promising results, AI implementation in nephrology is hindered by challenges. Clinical datasets often contain biases reflecting socioeconomic, racial, and regional disparities, which can propagate through AI models, leading to inequitable care. Lack of standardized data collection and variations in practice patterns further complicate model generalizability (18). Model interpretability remains a concern, as many AI algorithms operate as "black boxes," making clinical decision-making opaque. Regulatory frameworks and ethical considerations around patient data privacy, informed consent, and AI accountability are evolving but require clearer guidelines (18,34). Additionally, integrating AI into clinical workflows demands training for clinicians, reliable software infrastructure, and demonstration of cost-effectiveness. Addressing these challenges is essential to translate AI advances into routine kidney care (34).

Conclusion

Artificial intelligence has ushered in a new era in kidney disease management by enhancing diagnosis, prognostication, pathology assessment, transplantation, and dialysis care. Current applications demonstrate improved accuracy and efficiency beyond traditional methods, heralding a shift toward personalized nephrology. Nevertheless, challenges, including bias, interpretability, and integration, need to be addressed. Future AI innovations, supported by collaborative research and ethical frameworks, promise to revolutionize kidney disease care and improve outcomes globally.

Authors' contribution

Conceptualization: Haideh Mosleh and Sahar Kavand.
Data curation: Sahar Kavand and Haideh Mosleh.
Investigation: Sahar Kavand and Farzaneh Futuhi.
Validation: Farzaneh Futuhi and Haideh Mosleh.
Supervision: All authors.
Writing–original draft: All authors.
Writing–review and editing: All authors.

Conflicts of interest

The authors declare that they have no competing interests.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors utilized Perplexity to refine grammar points and language style in writing. Subsequently, the authors thoroughly reviewed and edited the content as necessary, assuming full responsibility for the publication's content.

Ethical issues

Ethical issues (including plagiarism, data fabrication, and double publication) have been completely observed by the authors.

Funding/Support

None.

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