



Artificial Intelligence in Nephrology: Current Applications and Emerging Opportunities

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Abstract

Artificial intelligence (AI) is increasingly influencing modern healthcare by enabling the analysis of large and complex clinical datasets. Nephrology is particularly suitable for AI applications because kidney care involves continuous laboratory monitoring, electronic health records, imaging, pathology, dialysis data, medication histories, and transplantation information. Machine learning, deep learning, natural language processing, and generative AI are being investigated for early disease detection, risk prediction, diagnosis, treatment optimization, and clinical decision support. Current applications include prediction of acute kidney injury, identification of patients at risk for chronic kidney disease progression, diabetic kidney disease assessment, renal imaging analysis, digital nephropathology, dialysis monitoring, and kidney transplantation. AI may also contribute to precision nephrology by integrating clinical, molecular, imaging, and longitudinal patient information. Emerging technologies such as multimodal AI, federated learning, digital biomarkers, and large language models may further expand the role of computational systems in kidney care. However, important challenges remain, including data quality, algorithmic bias, lack of external validation, limited interpretability, privacy concerns, regulatory uncertainty, and integration into clinical workflows. AI should therefore be regarded primarily as a tool for augmenting clinical expertise rather than replacing nephrologists. Future research should focus on prospective validation, patient-centered implementation, equitable performance, and demonstration of meaningful improvements in clinical outcomes. Responsible integration of AI could ultimately support earlier diagnosis, individualized risk assessment, more efficient healthcare delivery, and improved outcomes for patients with kidney disease.

Keywords: Artificial Intelligence; Machine Learning; Nephrology; Acute Kidney Injury; Chronic Kidney Disease; Diabetic Kidney Disease; Dialysis; Kidney Transplantation; Precision Medicine; Digital Health

Introduction

Kidney diseases represent a major global health challenge and include a wide spectrum of acute and chronic disorders. Clinical nephrology relies on the interpretation of numerous variables, including serum creatinine, estimated

glomerular filtration rate (eGFR), albuminuria, electrolytes, blood pressure, medication exposure, imaging, pathology, and longitudinal clinical history. The large amount of information generated during routine kidney care creates an environment in which artificial intelligence (AI) may provide useful analytical support [1].

AI refers broadly to computational methods capable of performing tasks associated with human intelligence, including learning, classification, pattern recognition, prediction, and language processing. Machine learning (ML) is an important branch of AI in which algorithms identify relationships within datasets and use these relationships to make predictions. Deep learning uses multilayer neural networks and is particularly useful for complex information such as medical images and digital pathology. Natural language processing (NLP) enables analysis of unstructured clinical documentation, while generative AI and large language models can assist with summarization, communication, documentation, and education.

The potential value of AI in nephrology is partly related to the limitations of conventional clinical assessment. Many kidney diseases develop gradually, and clinically important changes may not become apparent until substantial injury has occurred. Predictive algorithms could identify patients at increased risk before conventional indicators become obvious. AI may also integrate information from multiple sources that are difficult to evaluate simultaneously [2].

Research has already investigated AI applications in acute kidney injury (AKI), chronic kidney disease (CKD), diabetic kidney disease (DKD), renal imaging, nephropathology, dialysis, and transplantation. However, most applications remain in developmental or early implementation stages. High performance in a retrospective dataset does not necessarily translate into clinical benefit. External validation, calibration, interpretability, fairness, and prospective evaluation are essential before widespread implementation.

This mini-review summarizes important current applications of AI in nephrology and highlights emerging opportunities, limitations, and priorities for future research.

Mini Review

Machine Learning and Nephrology

Machine learning methods can analyze large numbers of clinical variables and identify relationships between patient characteristics and outcomes. Supervised learning is commonly used when the outcome is predefined, such as AKI, kidney failure, hospitalization, or mortality. Common algorithms include logistic regression, decision trees, random forests, support vector machines, gradient-boosting methods, and neural networks [3].

Unsupervised learning can identify groups of patients with similar characteristics without requiring a predefined outcome. This approach may help identify clinically

meaningful CKD phenotypes or subgroups with different disease trajectories.

The principal advantage of machine learning is its ability to analyze complex relationships and potentially capture nonlinear interactions. However, increasing model complexity does not automatically produce better clinical performance. Simple models may perform similarly to sophisticated algorithms when datasets are small or predictors are well established [4].

Artificial Intelligence in Acute Kidney Injury

AKI is a major target for AI research because early recognition may provide an opportunity for preventive intervention. Serum creatinine is an important marker of kidney dysfunction, but it may rise only after significant injury has already occurred. Electronic health records contain additional information that may signal impending AKI, including changes in blood pressure, medications, fluid balance, laboratory measurements, and clinical status.

Machine-learning models have been developed to predict AKI in hospitalized and critically ill patients. These models may identify high-risk patients before conventional diagnostic criteria are fulfilled.

The clinical value of early prediction depends on the response to an alert. If an AI system identifies a patient at high risk, clinicians may review nephrotoxic medications, assess volume status, optimize hemodynamics, or increase monitoring. However, excessive alerts may produce alarm fatigue [5].

Future research should therefore move beyond prediction accuracy and determine whether AI-supported AKI prediction actually reduces kidney injury, dialysis requirements, hospital length of stay, or mortality.

AI in Chronic Kidney Disease

CKD progression varies considerably between individuals. Patients with similar eGFR values may have different risks of rapid progression because of differences in albuminuria, diabetes, hypertension, cardiovascular disease, age, medication exposure, and underlying kidney pathology [6].

AI models can potentially integrate these variables with longitudinal clinical data to predict future kidney function decline or kidney failure. Such prediction could help identify patients who require closer follow-up or earlier preparation for kidney replacement therapy.

AI may also assist in identifying patients at risk of cardiovascular complications, hospitalization, and mortality.

An important emerging application is individualized CKD monitoring. Instead of relying solely on disease stage, predictive systems could estimate an individual's probability of progression and support personalized follow-up strategies.

Nevertheless, conventional markers remain essential. AI should complement established indicators such as eGFR and albuminuria rather than replace them.

AI and Diabetic Kidney Disease

Diabetes is one of the major causes of CKD worldwide. Early identification of individuals at high risk for DKD could allow closer monitoring and timely intervention.

AI-based models have incorporated demographic characteristics, glycemic measurements, kidney function, albuminuria, medications, comorbidities, and longitudinal electronic health record data. Research has demonstrated the feasibility of using machine learning to predict DKD development and progression [7].

Future models may incorporate genomic, proteomic, metabolomic, imaging, and wearable-device information. Such integration could help identify different biological patterns of DKD.

Another promising area is treatment response prediction. Patients with similar clinical characteristics may respond differently to therapies. AI could potentially identify individuals most likely to benefit from specific therapeutic strategies [8].

However, prediction of treatment response requires carefully designed prospective studies because associations identified by machine learning do not necessarily demonstrate causation.

AI in Renal Imaging

Renal imaging provides another important application of AI. Ultrasound, computed tomography, magnetic resonance imaging, and other imaging techniques contain information that can potentially be analyzed automatically.

AI systems can assist with kidney segmentation, measurement of kidney size and volume, cyst detection, lesion classification, and quantitative assessment of structural changes.

In autosomal dominant polycystic kidney disease, for example, kidney volume is an important indicator of disease

burden and progression. Automated segmentation could reduce the time required for measurements and improve reproducibility [9].

Deep-learning approaches may also identify imaging features that are difficult to quantify manually. Integration of imaging with clinical and laboratory information could provide more comprehensive disease-risk assessment.

However, imaging models may perform differently when applied to images obtained using different scanners, acquisition protocols, or patient populations. External validation is therefore essential.

AI in Nephropathology

Kidney biopsy interpretation is an important component of diagnosing glomerular, vascular, and tubulointerstitial diseases. Digitalization of pathology has created opportunities for computational analysis of whole-slide images [10].

AI can potentially identify glomeruli, quantify fibrosis, evaluate tubular injury, measure inflammatory changes, and classify morphological patterns. Automated quantitative pathology may reduce interobserver variability and provide reproducible measurements.

The combination of pathology images with clinical and molecular data is particularly promising. AI could potentially connect histological features with prognosis or treatment response.

Despite these opportunities, AI should currently be regarded as an assistive technology rather than a replacement for nephropathologists. Renal pathology requires integration of microscopy with clinical information, serology, immunofluorescence, electron microscopy, and other investigations.

AI in Dialysis

Dialysis treatment generates large amounts of data, including blood-flow rates, ultrafiltration rates, treatment duration, pressures, blood pressure measurements, and laboratory results. These data provide opportunities for predictive monitoring [7].

One important target is intradialytic hypotension. AI may identify patients at increased risk before blood pressure declines and could support preventive adjustments.

Other potential applications include prediction of hospitalization, treatment intolerance, vascular access problems, inadequate dialysis, and mortality [1].

AI may eventually support individualized dialysis prescriptions by considering interdialytic weight gain, residual kidney function, blood pressure patterns, treatment tolerance, and biochemical parameters.

However, automated recommendations must remain under clinical supervision because dialysis decisions involve competing risks and require patient-specific judgment.

AI in Kidney Transplantation

Kidney transplantation involves complex decisions concerning donor selection, recipient risk, graft function, rejection, immunosuppression, and long-term graft survival.

Machine learning has been investigated for predicting delayed graft function, acute rejection, graft failure, infection, hospitalization, and mortality. AI has also been applied to transplant pathology and imaging.

One promising direction is dynamic monitoring of graft health. Instead of evaluating individual measurements independently, AI could integrate serum creatinine, immunological information, biopsy findings, medications, and other longitudinal variables [2-5].

AI may also contribute to immunosuppression management by estimating risks associated with under- or over-immunosuppression.

However, transplantation datasets can be highly institution-specific. Differences in immunosuppressive protocols, donor populations, organ allocation systems, and follow-up practices can limit generalizability.

Emerging Opportunities

Precision Nephrology

Precision nephrology aims to provide individualized assessment and treatment rather than relying exclusively on population-level classifications.

AI can potentially integrate clinical, laboratory, imaging, pathology, genetic, and molecular information to identify distinct patient phenotypes.

For example, two patients with the same CKD stage may have very different mechanisms of disease and progression risks. AI-based clustering may identify these differences and support more individualized monitoring and treatment.

The ultimate objective is to move from simply asking whether a patient has kidney disease to determining why

the disease is progressing and which intervention is most appropriate.

Multimodal AI

Future AI systems are likely to combine multiple data types rather than relying on a single source.

A multimodal kidney-care system could integrate:

- Laboratory Measurements;
- Electronic Health Records;
- Imaging;
- Pathology;
- Genomic Information;
- Medications;
- Wearable-Device Data; And
- Patient-Reported Outcomes.

Such systems could provide a more comprehensive representation of kidney health. However, combining datasets with different formats, time intervals, and missing-data patterns remains technically challenging.

Generative AI and Large Language Models

Generative AI has introduced new possibilities for clinical documentation, education, communication, and research.

In nephrology, LLMs may assist with summarizing patient histories, extracting information from medical records, preparing educational materials, organizing literature, and drafting clinical documentation.

Generative AI may also help patients understand complex kidney-related information using simpler language.

However, LLMs can produce incorrect or fabricated information. Consequently, clinical outputs should always be reviewed by qualified professionals. Generative AI should currently be viewed as an assistant rather than an autonomous clinical decision-maker [5,6].

Federated Learning and Data Privacy

Healthcare institutions often cannot freely exchange patient-level information because of privacy, governance, and regulatory requirements.

Federated learning provides a potential approach in which algorithms are trained across multiple institutions while patient data remain locally stored. This could allow larger and more diverse datasets to contribute to model development without requiring centralized transfer of all

patient records.

For rare kidney diseases, multicenter collaboration could be particularly valuable because individual institutions may have relatively small patient populations.

Discussion

AI has considerable potential to transform nephrology, primarily because kidney medicine generates extensive longitudinal data. Prediction of AKI and CKD progression, analysis of DKD, digital pathology, renal imaging, dialysis monitoring, and transplantation represent some of the most active areas of investigation.

Nevertheless, important limitations must be recognized. First, AI systems are highly dependent on the quality of training data. Missing values, inaccurate documentation, inconsistent coding, and differences in measurement techniques can affect performance.

Second, algorithmic bias may occur when training datasets do not adequately represent the populations in which the model will eventually be used. A model that performs well in one demographic or healthcare setting may not perform equally well elsewhere.

Third, many studies are retrospective. Retrospective performance does not establish that implementation will improve patient outcomes. Prospective clinical trials and real-world implementation studies are needed.

Interpretability is another important issue. Clinicians need to understand the context and limitations of AI-generated predictions. An unexplained risk score may be less useful than a system that identifies the principal factors contributing to the prediction and communicates uncertainty.

Clinical workflow must also be considered. AI alerts that are too frequent may create alert fatigue, whereas predictions that do not lead to a defined clinical action may have little practical value.

Ethical and regulatory issues are increasingly important as AI becomes integrated into healthcare. Patient privacy, informed use of data, cybersecurity, accountability, transparency, and equitable access must be incorporated into AI development.

Importantly, AI should not be viewed as a substitute for nephrologists. Clinical medicine involves communication, contextual reasoning, ethical judgment, and consideration of patient preferences. AI is better positioned as a tool that can extend clinicians' analytical capabilities.

The future success of AI in nephrology will therefore depend less on increasingly complex algorithms and more on whether these systems can be safely integrated into clinical practice and produce meaningful improvements in patient outcomes.

Future Perspectives

Several priorities should guide future AI research in nephrology. First, external validation should become routine. Models should be tested using independent populations from different institutions and healthcare systems. Second, prospective studies are needed. Research should determine whether AI changes clinical decisions and improves patient outcomes rather than reporting predictive performance alone. Third, fairness must be evaluated. AI systems should be assessed across relevant demographic and clinical subgroups. Fourth, interpretability should be improved. Clinicians should receive understandable information about predictions and their uncertainty. Fifth, patient participation should increase. Patients should have opportunities to influence how their data are used and which AI applications are considered clinically valuable. Sixth, responsible use of generative AI is essential. LLMs should be evaluated for accuracy, hallucinations, privacy, bias, and reproducibility before being incorporated into clinical workflows.

Finally, AI research should consider low-resource healthcare environments. Technologies that can support early detection and specialist triage may help address shortages of nephrology services, provided that they are affordable, accessible, and appropriately validated.

Conclusion

Artificial intelligence is becoming an increasingly important area of nephrology research and has potential applications across the entire kidney-care pathway. Current research includes AKI prediction, CKD progression assessment, diabetic kidney disease, renal imaging, digital nephropathology, dialysis monitoring, and kidney transplantation. Emerging approaches involving multimodal AI, precision nephrology, federated learning, digital monitoring, and generative AI may further expand these applications.

Despite promising results, clinical adoption requires more than high predictive accuracy. AI systems must demonstrate generalizability, calibration, fairness, safety, interpretability, and clinical usefulness. Prospective studies are particularly important for determining whether AI actually improves patient outcomes.

The most appropriate future model is one in which AI and nephrologists work together. AI can process large datasets, identify patterns, and provide risk estimates, while nephrologists contribute clinical reasoning, contextual interpretation, ethical judgment, and patient-centered decision-making. When developed and implemented responsibly, AI could support earlier recognition of kidney disease, improve risk stratification, reduce workflow burdens, and contribute to more personalized kidney care.

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