



Precision Nephrology: Moving Toward Individualized Prediction and Prevention

Shetty T*, Melanie S and Rose F

Department of Urology, Associate Professor, Indiana University, USA

***Corresponding author:** Tina Shetty, Department of Urology, Associate Professor, Indiana University, USA

Perspective

Volume 10 Issue 3

Received Date: August 14, 2025

Published Date: September 01, 2025

Abstract

Chronic kidney disease (CKD) is a heterogeneous and progressive condition characterized by substantial variation in its causes, rates of progression, treatment responses, and long-term outcomes. Conventional nephrology practice has largely relied on population-level risk factors, estimated glomerular filtration rate, albuminuria, comorbidities, and clinical staging to guide diagnosis and management. Although these approaches remain essential, they do not fully capture the biological and clinical diversity of individual patients. Precision nephrology represents an emerging paradigm that seeks to move beyond generalized risk assessment toward individualized prediction, prevention, and treatment. Precision nephrology may be particularly valuable across the continuum of CKD, from individuals with risk factors but no established kidney disease to patients with advanced CKD and kidney failure. However, substantial challenges remain, including data quality, external validation, interpretability, health disparities, cost, privacy, infrastructure, and uncertainty regarding clinical utility. Importantly, precision nephrology should not be viewed solely as the application of advanced technology. Its ultimate objective should be to provide the right intervention to the right patient at the right time while improving meaningful clinical outcomes.

Keywords: Precision Nephrology; Chronic Kidney Disease; Precision Medicine; Individualized Risk Prediction; Kidney Disease Progression; Biomarkers; Artificial Intelligence; Personalized Prevention; Digital Health; Renal Outcomes

Introduction

Chronic kidney disease represents one of the major long-term challenges facing modern healthcare. Its increasing prevalence is closely associated with population aging, diabetes, hypertension, cardiovascular disease, obesity, environmental exposures, and changing lifestyles. CKD is not a single disease but a broad clinical syndrome resulting from multiple biological pathways and underlying conditions. Patients with apparently similar levels of kidney dysfunction may experience markedly different clinical trajectories. Some individuals remain stable for many years, whereas others experience rapid loss of kidney function, cardiovascular complications, acute kidney injury, kidney

failure, or premature mortality [1].

Current approaches to CKD classification and management have provided an important foundation for improving patient care. Estimated glomerular filtration rate (eGFR) and albuminuria are widely used to categorize disease severity and estimate risk. Clinical guidelines additionally incorporate blood pressure, diabetes status, cardiovascular disease, medications, and other established risk factors. These measures are practical and relatively inexpensive, but they represent only a limited portion of the biological information that determines an individual's kidney disease trajectory [2].

The concept of precision medicine emerged from the recognition that individuals with the same clinical diagnosis may differ substantially at molecular, genetic, environmental, and behavioral levels. In oncology, cardiology, pharmacology, and other specialties, precision approaches have increasingly been explored to identify disease subtypes and optimize therapeutic decisions. Nephrology is beginning to undergo a similar transformation [3].

Precision nephrology can be understood as the application of individualized, multidimensional information to predict kidney disease, identify mechanisms of injury, prevent progression, and guide treatment. Rather than asking only whether a patient has CKD, precision nephrology seeks to determine why the disease developed, how rapidly it is likely to progress, which complications are most probable, and which interventions are most likely to benefit that particular patient.

Why Precision Nephrology Is Needed

Heterogeneity of Chronic Kidney Disease

One of the strongest arguments for precision nephrology is the biological heterogeneity of CKD. CKD can result from diabetes, hypertension, glomerular diseases, inherited disorders, autoimmune conditions, congenital abnormalities, obstructive diseases, infections, toxic exposures, and numerous other causes. Even within a single diagnostic category, disease mechanisms can differ substantially.

Diabetic kidney disease, for example, is traditionally recognized through clinical parameters such as albuminuria and declining eGFR. However, not all patients with diabetes develop kidney disease, and not all individuals with diabetic kidney disease follow the same progression pattern. Some experience substantial albuminuria with relatively preserved filtration, while others experience declining kidney function with limited albuminuria [4].

These differences indicate that a simple classification based on conventional clinical measurements may not fully represent underlying biological processes. Precision nephrology seeks to identify additional characteristics that explain this variability.

Limitations of Conventional Risk Prediction

Existing risk prediction tools have substantially improved the ability of clinicians to estimate future outcomes. Nevertheless, many models rely on a relatively small number of variables. Age, sex, eGFR, albuminuria, blood pressure, diabetes, and cardiovascular disease are important predictors, but they do not capture every relevant biological

and environmental factor [5].

Kidney disease progression may be influenced by inflammation, fibrosis, endothelial dysfunction, oxidative stress, metabolic abnormalities, immune responses, genetic susceptibility, medication exposure, dietary patterns, social circumstances, and environmental factors.

Precision Approaches Across CKD Stages

Precision nephrology should not be limited to patients with advanced kidney disease. Its greatest potential may exist across the entire kidney health continuum.

Individuals at Risk Before CKD

The first stage of precision nephrology may involve identifying individuals who have risk factors but do not yet meet conventional definitions of CKD [1].

Diabetes, hypertension, obesity, cardiovascular disease, family history, aging, recurrent acute kidney injury, and certain medication or environmental exposures may increase future kidney disease risk. However, the degree of risk varies considerably among individuals with the same risk factor.

Future precision screening strategies could combine clinical information with genetic susceptibility, family history, metabolic characteristics, biomarkers, and longitudinal health data to classify individuals according to personalized kidney risk.

Instead of applying identical screening schedules to everyone, healthcare systems could potentially provide different levels of surveillance based on predicted risk.

For example, an individual with multiple interacting risk factors could receive more frequent kidney function and albuminuria assessments, while a lower-risk individual could follow a less intensive monitoring schedule.

This approach could make screening more efficient while improving the likelihood of detecting clinically important disease [5].

Challenges and Limitations

Data Quality and Standardization

Precision nephrology depends on high-quality data. Clinical records often contain missing values, inconsistent documentation, differences in laboratory methods, and varying follow-up intervals.

An algorithm trained on incomplete or biased information may generate unreliable predictions. Standardization of data collection and terminology will therefore be essential.

External Validation

Many predictive models demonstrate impressive performance during development but perform less well when applied to different populations. A model trained using data from one healthcare system may not generalize to another because patient characteristics, disease prevalence, laboratory practices, socioeconomic conditions, and treatment patterns differ. Independent external validation should therefore be considered a fundamental requirement before widespread clinical implementation.

Future Directions

The future of precision nephrology will likely involve the convergence of several technological and clinical developments.

Integrated Multidimensional Risk Profiles

Future systems may combine conventional clinical measurements with molecular biomarkers, genetic information, imaging, environmental exposures, lifestyle characteristics, medication history, and patient-generated data.

Rather than producing a single generic CKD risk score, such systems could generate individualized profiles describing risks of progression, cardiovascular complications, acute kidney injury, hospitalization, and kidney failure.

The usefulness of such systems will depend on whether the information can be translated into actionable clinical recommendations.

Longitudinal Monitoring

Precision nephrology should increasingly focus on changes over time. Serial measurements can provide information about disease velocity and treatment response that cannot be obtained from isolated laboratory values.

Conclusion

Precision nephrology represents an important

opportunity to reshape the prevention and management of kidney disease. CKD is highly heterogeneous, and conventional measures alone cannot fully explain why some individuals remain stable while others rapidly progress to kidney failure or develop severe complications.

The integration of clinical information with biomarkers, genetics, imaging, longitudinal measurements, digital health data, and artificial intelligence may enable more individualized prediction and earlier intervention. Precision approaches can potentially be applied across the entire CKD continuum, from individuals at risk to patients with advanced disease, dialysis dependence, and kidney transplantation.

Nevertheless, precision nephrology should not be defined simply by the amount of data collected or the sophistication of an algorithm. Its value ultimately depends on whether it improves clinical decisions and patient outcomes. Data quality, external validation, algorithmic fairness, interpretability, privacy, cost, and accessibility remain major considerations.

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