Review

The Application Prospects of Artificial Intelligence in the Comprehensive Management of Patients with Cardiovascular-Kidney-Metabolic Syndrome

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Abstract:

Cardiovascular disease (CVD), chronic kidney disease (CKD), and metabolic diseases are closely interrelated and frequently co-occur, significantly increasing the complexity of disease management, posing serious threats to human health, and representing a major public health challenge in China. In response, the American Heart Association has released a Presidential Advisory on Cardiovascular-Kidney-Metabolic (CKM) syndrome, aiming to enhance the collaborative management of patients with these comorbidities. However, current clinical management practices for CKM syndrome face multiple challenges, and the management status is suboptimal. Integrated interventions, interdisciplinary collaboration, and innovative therapies are required to improve outcomes in patients with CKM syndrome [38].There is an urgent need to introduce efficient and precise scientific technologies to assist in the comprehensive management of CKM syndrome patients to reduce cardiovascular and renal risks and improve prognoses. In recent years, artificial intelligence (AI) technology has rapidly advanced in the medical field, methods such as machine learning (ML) have, to a certain extent, enhanced clinicians' ability to obtain accurate diagnoses and make sound clinical decisions [13， 24], showing promise as a powerful tool to further enhance the efficiency of clinical management for CKM syndrome. This article will elaborate on the epidemiological status, current management challenges, and the application prospects of AI in CKM syndrome management, providing insights for promoting the integration of AI and

CKM syndrome care.

Keywords: Artificial Intelligence; CKM Syndrome; Early Screening; Risk Prediction; Clinical Decision Support

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1.Epidemiological Status of CKM Syndrome

Cardiovascular-Kidney-Metabolic (CKM) syndrome is defined as a systemic disorder initiated by pathophysiological interactions among obesity, type 2 diabetes mellitus (T2DM), CKD, and cardiovascular disease [1]. Over the past 40 years, the incidence of metabolic disorders (including diabetes, dyslipidemia, hypertension, obesity, etc.) in China has been rising annually, making China the country with the largest population affected by metabolic abnormalities globally. The epidemic of CKM syndrome in China is becoming increasingly severe [2]. According to findings from a nationwide cross-sectional study, the prevalence of chronic kidney disease (CKD) among adults in China is as high as 10.8%, affecting approximately 119.5 million individuals [11].Meanwhile, another study revealed that the total prevalence of diabetes among Chinese adults was 10.9% in 2013, with a prediabetes prevalence of 35.7% [34].Results from the Chronic Disease Cohort Study of a natural population in communities in the Beijing-Tianjin-Hebei region (2017-2019) showed that among Chinese adults aged 18-90, only about 11.1% of individuals were free of any CKM-related risk factors [3]. The prevalence rates for each CKM stage were: Stage 1 (risk factors only, e.g., obesity/prediabetes) 15.5%, Stage 2 (established metabolic disease or moderate/high-risk CKD) was highest at 48.1%, and Stage 3 and 4 (subclinical CVD and clinical CVD, respectively) combined reached 25.3%. This indicates that over 88% of the adult population is at some stage within the CKM spectrum, with the prevalence of each component disease continuing to rise, constituting a vast patient population. Data from the Global Burden of Disease Study further confirm that metabolic diseases and their related cardiorenal complications, such as diabetes, have become one of the leading causes of disability-adjusted life years (DALYs) lost [12]. Among CKM syndrome patients, diabetes and hypertension are the primary risk factors leading to cardiovascular and renal damage [39]. Patients with both diabetes

and hypertension have a 76% increased risk of heart failure, an 89% increased risk of myocardial infarction, a 57% increased risk of stroke, a 57% increased risk of overall adverse cardiovascular events, and a 72% increased risk of all-cause mortality [4-7]. Therefore, clinicians should prioritize the evaluation of blood pressure control, assessment of cardiovascular risk, and adjustment of treatment strategies in patients with comorbid diabetes and hypertension [40].The large population affected by CKM syndrome and its associated harms not only significantly reduce patients' quality of life but also pose severe challenges to societal healthcare resources [11-12,14], making it a major public health problem in China. Therefore, how to effectively reduce the risk of adverse cardiovascular and renal events in the CKM syndrome population has become a significant challenge and research focus in its management.

2. Current Clinical Management Status of CKM Syndrome is Suboptimal

Currently, clinical management practices for CKM syndrome still face severe challenges, and the management status is not optimistic. This challenge is reflected in two aspects:

2.1 Patient Level: Insufficient Disease Awareness and Poor Treatment Adherence Leading to Missed Opportunities for Early Intervention. Firstly, CKM syndrome often presents asymptomatically or with atypical symptoms in its early stages [1] (e.g., mildly elevated blood pressure, abnormal glucose metabolism, microalbuminuria, overweight). Patients often lack sufficient awareness of their own risks. This low perceived risk leads to low motivation for proactive screening; even if abnormalities are detected through physical examination or incidental testing, patients often delay seeking medical attention or refuse further evaluation due to the lack of immediate discomfort. Secondly, even after patients enter the healthcare system and receive a diagnosis, their treatment adherence is generally poor. Managing CKM syndrome requires long-term, often lifelong intervention, but many

patients struggle to adhere to standardized treatment due to factors such as inconspicuous short-term effects, concerns about drug side effects, or psychological resistance. Crucially, patients often fail to recognize the critical role of early intensive intervention in preventing cardiac and renal endpoint events, only seeking treatment after irreversible damage such as myocardial infarction, heart failure, or end-stage renal disease occurs. At this point, not only do treatment costs increase substantially, but the prognosis also significantly worsens. Studies have indicated a significant association between patients' health literacy levels and the progression rate of chronic kidney disease (CKD) [15]. Patients with low health literacy face a 2.3-fold increased risk of accelerated renal function decline.This behavior pattern of "emphasizing treatment over prevention" greatly limits the effectiveness of CKM syndrome prevention and control, exacerbating the overall disease burden.

2.2 Physician Level: Difficulty Providing Outcome-Oriented Comprehensive Management Due to Specialty Limitations and Lack of Integrated Concepts.

Current clinical practice remains predominantly specialty-oriented and fragmented. Different specialists often focus only on abnormal indicators within their own domain (e.g., blood glucose, blood pressure, eGFR), lacking a patient-centered holistic perspective, which leads to treatment plans that are not comprehensive, scientific, or individualized. More importantly, most physicians fail to prioritize "improving cardio-renal outcomes" as the core management goal, overlooking the importance of early intervention and comprehensive control of multiple risk factors. Primary care physicians, as gatekeepers of health, face immense challenges in keeping their knowledge updated and in their comprehensive decision-making capabilities when confronted with such a complex syndrome. Therefore, there is an urgent need to explore new tools to assist clinicians in achieving early screening, accurate assessment, and comprehensive management of CKM syndrome patients,

breaking down specialty barriers, improving the efficiency of early intervention, reducing cardiovascular and renal risks, and improving patient prognosis.

3. Application Prospects of Artificial Intelligence (AI) in CKM Syndrome Management

In recent years, the rapid development of medical artificial intelligence (AI) technology has provided new opportunities for optimizing early intervention and comprehensive management of patients with CKM syndrome.

3.1 Application of AI in Early Screening and Risk Prediction for CKM Syndrome

Early detection and intervention in CKM syndrome are associated with greater clinical benefits. For instance, early intervention in CKM Stage 1 (excess or dysfunctional adiposity) and Stage 2 (with metabolic abnormalities and CKD) can significantly delay progression to Stage 3 (with subclinical CVD) and Stage 4 (with clinical CVD), thereby reducing the risk of endpoint events such as heart failure and end-stage renal disease [8]. Early screening, diagnosis, and intervention play a major role in CKM syndrome management. AI, leveraging big data and deep learning technologies, can integrate data from electronic health records—including metabolic parameters, cardiac and renal function, and social determinants of health—to build risk prediction models. These models assess an individual's risk of cardiovascular and renal events, provide early warnings to patients, and aid in the screening of high-risk populations [9，22]. Furthermore, machine learning-based dynamic prediction models can integrate multi-dimensional risk factors (e.g., blood pressure, blood glucose, lipids, BMI, lifestyle habits) to dynamically adjust risk levels. This helps doctors and patients understand disease progression trends, enables patients to identify risk factors that are not yet under control, and provides personalized, scientifically-guided intervention recommendations for high-risk individuals [10,16,17，35]. Consequently, this enhances patient awareness of the

disease and its risks, improves adherence, facilitates a shift from "passive treatment" to "active health management," and promotes proactive early intervention to improve prognosis.Research has demonstrated that AI-based prediction models excel at identifying high-risk CKD patients, achieving an area under the curve (AUC) of 0.85–0.93 [18], which is significantly superior to conventional risk assessment tools [32].Meanwhile, artificial intelligence can improve the accuracy of cardiovascular disease risk prediction using routine clinical data [25].

3.2 Application of AI in Clinical Decision Support for CKM Syndrome

It is also possible to develop specialized large language models for CKM syndrome. Using Natural Language Processing (NLP) technology, AI can deeply learn and integrate the latest guidelines and authoritative literature from cardiology, nephrology, endocrinology, and other relevant fields. This allows for the construction of a vast, structured knowledge graph that provides physicians with standardized, guideline-concordant treatment pathway recommendations. Simultaneously, it can present key evidence-based rationales, enabling doctors to access comprehensive and precise decision-making support in real-time. This helps narrow the gap in CKM knowledge and practice among physicians at different levels of healthcare institutions and with different specialty backgrounds, maximizing diagnostic and therapeutic efficiency, and promoting a shift towards precision and intelligent transformation in care models [20 , 30].Thus, it enables comprehensive and efficient management of CKM-related metabolic risk factors, integrates all relevant risk factors to provide patients with the most suitable diagnosis and treatment plans, and ultimately improves prognosis.Furthermore, emerging federated learning techniques enable the training of more robust AI models using multi-center data while preserving data privacy, offering a potential solution to the data isolation problem in medical AI development [19].Clinical decision support systems (CDSS) contribute to

improving the quality of care in the primary prevention of cardiovascular disease [37]. AI models hold promise for achieving true precision medicine by not only predicting disease progression but also detecting heterogeneity in treatment response [26, 33].

AI applications have already yielded significant results in various sub-specialties of cardiovascular disease, extensively involving risk prediction, early diagnosis, clinical decision support, and more. These advancements have made cardiovascular disease diagnosis more precise and rapid, and risk prediction more accurate[21，27，28，31].Advances in natural language processing have enabled the extraction of CKM-relevant information from unstructured electronic health records [20], thereby enriching the data dimensions available for CKM risk assessment.Building AI-based models for CKM risk prediction and comprehensive management aims to achieve early identification, risk stratification, and personalized intervention for CKM patients. This facilitates a transition from the traditional "disease treatment" model to "early intervention and comprehensive management of risk factors," holding significant strategic importance for reducing the incidence of endpoint events and alleviating the societal healthcare burden, with broad prospects[36].The development of medical artificial intelligence (AI) in imaging has become increasingly sophisticated, providing automated and interpretable tools for disease detection, tracking, and exploration [29]. Although the application of AI in the management of CKM syndrome holds broad prospects, vigilance is warranted against potential inflated expectations during its development. Emphasis should be placed on its clinical utility and interpretability [23, 33].

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