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Radiopharmaceutical administration in chronic kidney disease; pharmacokinetic challenges, dosimetry, and safety considerations

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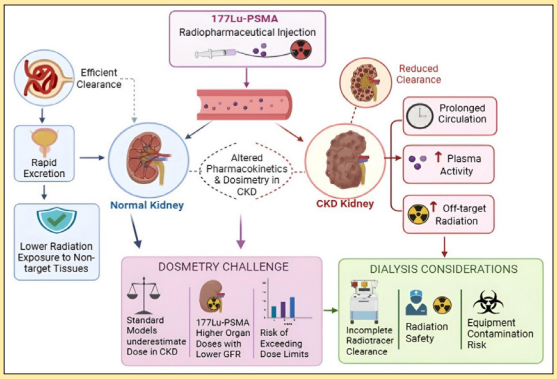
ABSTRACT

Chronic kidney disease (CKD) significantly alters the pharmacokinetics of radiopharmaceuticals, primarily through reduced renal clearance that prolongs systemic circulation and modification of biodistribution patterns. This condition impaired excretion elevates plasma concentrations of both diagnostic and therapeutic radiotracers, potentially increasing radiation exposure to non-target tissues while compromising image quality or therapeutic efficacy. Dosimetry becomes particularly complex in CKD patients, as standard models assuming normal renal function underestimate radiation doses to kidneys and other organs. One of them is ^{177}Lu-PSMA [lutetium-177-(prostate-specific membrane antigen)], which demonstrated higher healthy tissue doses in patients with reduced glomerular filtration rates. The kidneys themselves face dual risks; as the clearance organs, they receive elevated radiation doses from retained radiopharmaceuticals, since pre-existing renal impairment may lower tolerance thresholds below the conventional 23 Gy limit established for peptide receptor radionuclide therapy. Furthermore, safety considerations necessitate individualized approaches, though evidence-based dosing guidelines remain scarce and inconsistent across radiopharmaceuticals. Patients on dialysis present additional challenges, as extracorporeal clearance may incompletely remove radiotracers while creating radiation safety concerns for healthcare staff and equipment contamination. Notably, certain agents exhibit nephrotoxic potential beyond radiation effects, particularly those with inherent renal retention properties. Despite these complexities, most diagnostic nuclear medicine procedures maintain favorable safety profiles in CKD when appropriately managed. Still critical knowledge gaps persist regarding optimal dose adjustments across CKD stages, long-term renal functional impacts of therapeutic radiopharmaceuticals, and standardized protocols for dialysis timing relative to administration, therefore future studies should prioritize prospective dosimetry studies and develop consensus guidelines to ensure safe, effective radiopharmaceutical use across the spectrum of renal impairment while balancing diagnostic/therapeutic benefits against cumulative radiation risks.



Review

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Implication for health policy/practice/research/medical education:
Radiopharmaceutical administration in chronic kidney disease (CKD) demands integrated policy, practice, and educational reforms. Health policies must establish CKD-specific dosing guidelines and radiation safety standards, accounting for altered pharmacokinetics and prolonged radionuclide retention. Clinically, practitioners require protocols for individualized dosimetry calculations, enhanced hydration strategies, and extended radiation safety counseling for patients and caregivers. Research priorities include prospective studies on organ-specific radiation doses in varying CKD stages, development of renal-clearance-adjusted dosing algorithms, and long-term safety data for novel theranostic agents. Medical education must incorporate nephrology-radiology interdisciplinary training, emphasizing on the pharmacokinetic principles in renal impairment, accurate dosimetry interpretation, and ethical risk-benefit communication. Regulatory agencies should mandate renal function stratification in radiopharmaceutical trials. Finally, a precision medicine framework, integrating renal function, dialysis status, and radiopharmaceutical properties is necessity to optimize diagnostic accuracy, therapeutic efficacy, and radiation safety while minimizing nephrotoxicity risks in this vulnerable population.

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Introduction

Chronic kidney disease (CKD) significantly alters the pharmacokinetics of several drugs, necessitating a thorough detection of drug properties, changed patient physiology, and pharmacokinetic principles for appropriate dosing (1). This approach allows for better medical care and minimizes adverse drug events due to variations in dosing (1). Despite the availability of some guidelines for dosing in renal disease, these guidelines may be based on limited data or not be widely applicable, emphasizing on the importance of consideration the pharmacokinetic principles (1). In both acute kidney injury (AKI) and CKD, drug clearance decreases, while the volume of distribution may remain constant or increase. Though these alterations develop gradually in CKD, they are dynamic in AKI, with recovery being possible depending on the etiology and treatment of AKI (2). Notably, the use of kidney replacement therapies further complicates efforts to quantify drug clearance during prescribing and dosing in AKI The conventional approach to approximating drug pharmacokinetics in CKD patients primarily considers changes in the estimated glomerular filtration rate (3). Nevertheless, chronic renal failure is a systemic disease that impacts numerous body systems (4). A more mechanistic approach to predict pharmacokinetics in CKD individuals consists of developing whole-body physiologically based pharmacokinetic (PBPK) models. These models can represent the disposition of various compounds, including those eliminated substance by glomerular filtration, across with active tubular secretion (5). In fact, adapting healthy adult models to CKD patients along with considering of changes in glomerular filtration rate, kidney volume, renal perfusion, hematocrit and plasma protein concentrations, and also gastrointestinal transit, will improve the exposure predictions of these agents. This integrated approach has shown notable improvement over conventional scaling methods, particularly in patients with advanced CKD (5). Pharmacokinetic properties are crucial for effective optimal pharmacotherapy. Previous authors found that, CKD influences medication pharmacokinetics (1). Studies evaluating sex differences in the pharmacokinetics of drugs for CKD treatment in children are lacking, making it challenging to extrapolate data from adult studies. Some studies suggest that girls generally have a higher prevalence and faster progression of CKD compared to boys, regardless of age (6,7). In addition, drug pharmacokinetics and pharmacodynamics is essential for guiding optimal medication regimens. Future kinetic studies are needed to evaluate the effect of sex on drug pharmacokinetics and pharmacodynamics in children with CKD too (8). In this narrative review, we sought to consider radiopharmaceutical use in chronic kidney disease by pharmacokinetic challenges, dosimetry and safety considerations.

Search strategy

A comprehensive literature search was conducted across multiple electronic databases, including PubMed, Google Scholar, the Directory of Open Access Journals (DOAJ), Web of Science, EBSCO, Scopus, and Embase, to identify relevant peer-reviewed studies. The following keywords and Medical Subject Headings (MeSH) terms were used, either alone or in combination: chronic kidney disease, acute kidney injury, ^{177}Lu-PSMA, lutetium-177, radiopharmaceutical, peptide receptor radionuclide therapy (PRRT), and drug pharmacokinetics. Boolean operators (AND, OR) were applied to refine and broaden the search as appropriate. No restriction was placed on publication date; however, only peer-reviewed articles published in English were considered eligible for inclusion. Studies were initially screened by title and abstract, followed by full-text review of potentially relevant articles. Reference lists of included studies were also manually examined to identify any additional sources not captured through the database search.

Radiopharmaceutical use in CKD

Patients with CKD face unique challenges when it comes to radiopharmaceutical use due to significant alterations in drug pharmacokinetics, complex dosimetry considerations, and specific safety concerns. These challenges necessitate a thorough consideration of how CKD impacts radiopharmaceutical disposition within the body, the methods for accurately assessing radiation doses to vital organs, and the potential for adverse effects (9). Therefore, the primary goal is to ensure both diagnostic accuracy and therapeutic efficacy while minimizing risks in a vulnerable patient population (9). Previous studies demonstrated that, changes in pharmacokinetics in CKD patients can lead to altered drug exposure, potentially resulting in either overdosing or underdosing, which may cause adverse drug reactions or therapeutic failure (2). Renal disease profoundly affects the absorption, distribution, metabolism, and elimination of drugs, which are collectively known as pharmacokinetics. These physiological effects vary among individuals and can be quantified in some cases (1). A strong interpretation of pharmacokinetic principles is crucial for designing rational drug dosing regimens to provide personalized medical care (10). In CKD, drug clearance generally decreases, while the volume of distribution may either remain unchanged or increase (2). Unlike AKI, where kidney function changes dynamically and complicates accurate drug clearance quantification, changes in drug clearance with CKD progresses more slowly (1,11). Kidney replacement therapies typically increase drug clearance, but the extent of this increase depends on the specific modality, its duration, the drug's properties, and the timing of drug administration (12). Nevertheless, changes in drug handling in kidney disease are not limited to reduced kidney clearance, and it is important to appreciate the potential scale of these derangements (2). In most cases, the initial dose given to CKD patients is the same as for patients with normal kidney function (3,13). Nonetheless, sometimes a higher loading dose is administered to quickly achieve therapeutic concentrations, followed by a lower maintenance dose, predominantly for anti-infective agents in patients with sepsis and AKI (14). Physiologically based pharmacokinetic modeling can help evaluate how CKD affects the disposition of non-renal cleared drugs, even those primarily cleared by the liver, such as those metabolized by cytochrome P450 (CYP)2C8 or transported by hepatic organic anion-transporting polypeptides (OATP)1B (15,16). A recent PBPK analysis suggested that OATP1B activity could be reduced by up to 60% in severe CKD, while changes in CYP2C8 activity were found to be negligible. This strengthened identification of CKD's impact on clearance pathways is crucial for optimizing the use of non-renal eliminated drugs in these patients (16). Recently, the US Food and Drug Administration (FDA) have issued guidance documents to address scientific and regulatory issues in studying the pharmacokinetics of drugs in patients with impaired renal function. These guidelines provide recommendations for evaluating both principally renally cleared and non-renally cleared drugs in subjects with renal impairment and for categorizing renal function using estimated glomerular filtration rate equations (1,17). Optimizing drug dosing requires a perception of how various intrinsic and extrinsic factors affect systemic drug exposure and response (18). Moreover, CKD is a significant intrinsic factor that can affect a patient's response to drugs by affecting the pharmacokinetic characteristics of a therapeutic drug and its metabolites (1,18). Delivering pharmacotherapy to CKD patients presents significant challenges beyond alterations in absorption, distribution, metabolism, and elimination, as many patients also take multiple medications daily (19). The risk of adverse drug reactions increases with each additional medication in their daily regimen (20). For radiopharmaceuticals used in renal function assessment, such as 131I-Hippuran (iodide-131 Hippuran) and 99mTc-MAG3, identification of pharmacokinetics is crucial (21-23). Regarding, 99mTc-MAG3 (99mTc-mercaptoacetyltriglycine), for example, is highly protein-bound and is primarily removed from plasma by the organic anion transporter 1 (OAT1). It is frequently used for renal scans, especially in patients with suspected obstruction and impaired renal function (24). While 99mTc-MAG3 has widely replaced radioiodine labeled hippurate for renal function studies, its biological properties differ, including higher protein binding, slower blood clearance, and higher tubular cell extraction efficiency (23). Despite these differences, 99mTc-MAG3 provides excellent image quality even with severely decreased renal function and can be used for quantitative measurement of effective renal plasma flow (25).

Focus on dosimetry in CKD individuals

Dosimetry considerations in CKD patients are complex due to the altered biodistribution and excretion of radiopharmaceuticals (9). Radiogenic nephropathy, a potential side effect, highlights the need for careful dosimetric analysis. In external beam radiotherapy, patient-individual dosimetric analyses are a useful tool to protect patients from side effects (26). However, individual dosimetry is not routinely used in patients treated with radiolabeled antibody fragments or polypeptides due to several challenges (27). In internal radiotherapy, tracers are not evenly distributed within organs, leading to non-uniform dose distributions, unlike the even dose distribution in external beam radiotherapy (28). Additionally, the dose rate of commonly used radionuclides

in internal radiotherapy is lower, and their radiation range differs, resulting in considerably different radiobiological effects compared to external beam radiotherapy (29). It seems that, more complex models are needed for clinical renal dosimetry in internal radiotherapy; while, consideration of the reasons for radiotracer accumulation in the kidney, recent developments in kidney dosimetry, and approaches to reduce renal uptake are crucial to prevent radiogenic nephropathy (30). Radiopharmaceuticals, which are pharmaceuticals labeled with radionuclides, are studied at a preclinical level in animals before human use to understand their biokinetics and estimate the irradiation delivered clinically (31). The biodistribution of radiopharmaceuticals in diseased and healthy organs is fundamental to nuclear medicine, providing diagnostically useful images or therapeutically beneficial local irradiation of tissue (9,32). In most procedures, biodistribution primarily related to the clearance of radiopharmaceuticals from the blood into organs, tissues, or lesions (33). Likewise, radiation is harmful, therefore assessing radiation toxicity for new radiopharmaceuticals is indispensable, while this calculation can be conducted using internal dose calculation methodologies (9). Specific radiopharmaceuticals are designed for renal function and anatomy investigations. These compounds can be categorized into those filtered by the glomerulus, those retained in renal tubules by proximal tubule receptor-mediated endocytosis, and those primarily secreted by renal tubules through organic anion transporters (22,32). Meanwhile, 131I-Hippuran and 99mTc-MAG3 are critical radiopharmaceuticals in renal scintigraphy (34). The clinical application of 99mTc-MAG3, including its pharmacokinetics and quantification of renal function, is well-established for renal diseases. This agent offers excellent image quality even in cases of severely decreased renal function and is used for effective renal plasma flow measurements (23).

Focus on safety considerations

Safety considerations are paramount when using radiopharmaceuticals in CKD patients, as they are a vulnerable population (9). The safety profile of radiopharmaceuticals can be affected by interactions with other medications (35). There is a general lack of consistent recommendations for radiopharmaceutical dosing in CKD patients, despite the potential for adverse effects and poor outcomes if dosages are not adjusted (9,36). Radiopharmaceuticals, which are radioactive substances used in medicine for diagnosis and treatment, are generally considered very safe because only tiny amounts are administered (31). However, little is known about adverse events, drug interactions, and their use in specific patient groups like those with renal insufficiency (31). A previous study investigating adverse events found that patients experienced adverse events with diagnostic radiopharmaceuticals more often than previously recorded, though most were mild and resolved quickly, such as a hot feeling, fatigue, or headache, with no serious adverse events reported (37). Radiopharmaceuticals, most often administered intravenously are radioactive compounds used for diagnostic or therapeutic purposes. They can induce adverse reactions and drug-to-drug interactions that may alter expected biodistribution, potentially affecting patient safety and diagnostic accuracy (31,38). Adverse reactions are relatively rare due to the small doses typically administered, and under-reporting is common. Establishing a reporting system, such as through an electronic form, can enhance the registration of adverse events (20). In fact, most radiopharmaceuticals can likely be used safely in patients with the rare metabolic disorder porphyria, though some may require preventive measures (9,39). However, for patients with impaired renal function, there is insufficient information regarding the safe use of radiopharmaceuticals, underscoring the need for further research (39). Finally, regarding outcomes, an increased awareness among patients and healthcare providers on drug safety aspects of radiopharmaceuticals is still crucial for improving patient outcomes (37). Peptide receptor radionuclide therapy (PRRT) using lutetium-177 (^{177}Lu)-based radiopharmaceuticals, such as ^{177}Lutetium-[DOTA^{0},Tyr^{3}]octreotate (^{177}Lu-DOTATATE) and ^{177}Lu-PSMA-617 [lutetium-177-(prostate-specific membrane antigen)-617 or (Pluvicto^{TM})], represents a growing therapeutic area in nuclear medicine and oncology, allowing for personalized medicine (40). While the efficacy of ^{177}Lu radiopharmaceuticals is well-reported, data on patient safety and management, especially in specific populations like those with CKD, are continuously being gathered and refined (41). Tailored approaches to enhance the risk-benefit trade-off of radioligand therapy are being explored to help clinicians and nuclear medicine staff establish safe and optimized procedures (40).

Conclusion

In summary, radiopharmaceutical use in chronic kidney disease presents several challenges requiring careful clinical consideration. Impaired renal function fundamentally alters pharmacokinetics, reducing clearance of the excreted radiotracers and prolonging their systemic circulation. This condition leads to increased radiation exposure to kidneys and non-target tissues, altered biodistribution, and potential diagnostic inaccuracies. Consequently, conventional dosimetry models derived from healthy populations become inadequate, necessitating patient-specific adjustments based on measured glomerular filtration rate and quantitative imaging. For therapeutic

radionuclides like ^{177}Lu-PSMA, cumulative renal radiation doses pose significant nephrotoxicity risks, demanding rigorous pre-therapy assessment and possibly dose fractionation or amino acid infusion for renal protection. Safety considerations must balance diagnostic/therapeutic benefits against heightened radiation risks in an already vulnerable population. Importantly, many radiopharmaceuticals themselves lack intrinsic nephrotoxicity, but their prolonged retention in CKD may exacerbate existing renal damage through radiation-induced injury. Hence, advancements should prioritize developing non-renal cleared alternatives, refining personalized dosimetry protocols incorporating kidney function metrics, and establishing evidence-based safety thresholds for different CKD stages. Likewise, collaboration among nuclear medicine physicians, nephrologists, and medical physicists is necessary to optimize radiopharmaceutical utilization in CKD patients. Thereby, with appropriate risk stratification, individualized dose adjustment, and vigilant monitoring, nuclear medicine procedures can be safely and effectively incorporated into CKD patient management.

Authors' contribution

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Visualization: Boretskaya Alisa and Gaffarov Usmon.
Writing–original draft: All authors.
Writing–review and editing: All authors.

Ethical issues

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

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