JURNAL VOKASI KESEHATAN

Article Review

Advancements in Biomarkers for Assessing Dialysis Efficiency: A Comprehensive Review

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ABSTRACT

This review discusses the recent development in biomarkers of dialysis efficiency in patients suffering from CKD and ESRD. The systematic review covered literature in the years 2019 to 2024 with emerging biomarkers and their clinical application along with innovative ways to detect the biomarkers. Traditional biomarkers are the urea reduction ratio (URR) and Kt/V, while newer biomarkers like β2-microglobulin, cystatin C, and fibroblast growth factor 23 (FGF23) receive increased recognition regarding their ability to better present patient health. These biomarkers could dramatically enhance personalization of treatment through precise adjustments in dialysis regimens that may promote better patient outcomes. All of these developments are further driven by technological advancements, for instance, optical sensors and point-of-care devices, for real-time and more sensitive detection of biomarkers. Indeed, the integration of these new biomarkers and technologies may revolutionize dialysis patient monitoring, enabling more tailored and effective strategies.

INTRODUCTION

Chronic kidney disease (CKD) and end-stage renal disease (ESRD) have been an emerging public health challenge worldwide, with an estimate of about 10% of the global population being affected by CKD, a number that has kept rising over the past few decades (Hill et al., 2016).[1] The prevalence of CKD is due to aging populations and the increasing incidence of comorbidities such as diabetes and hypertension, which are primary risk factors for kidney disease. By 2019, an estimated more than 850 million people worldwide had some stage of kidney disease; meanwhile, CKD was newly ranked as the 12th cause of death (GBD Chronic Kidney Disease Collaboration, 2020). ESRD is the last most extreme stage of CKD, which requires life-support interventions like dialysis or renal transplant, both of which add substantial medical and fiscal challenges to health care delivery services.

Dialysis forms the foundation of ESRD management because it serves as an adjunct to some renal function, replacing many functions performed by the failing kidneys. The traditional monitoring methods have several limitations and shortcomings with regards to their utility in measuring the adequacy of dialysis; these biomarkers have largely been restricted to only URR and Kt/V. These traditional markers essentially measure the removal of small solutes, such as urea, but cannot assess the clearance of bigger and more complex molecules, which are important for patient outcomes (Daugirdas, 2015).[2]The evidence emerging for advanced biomarkers such as β2-microglobulin, cystatin C, and fibroblast growth factor 23 (FGF23) may bring about a better insight into kidney function and the overall health status of the patient, potentially resulting in tailored and potentially improved dialysis regimens.

Improvement in care dialysis is urgently called for as the mortality continues to remain high in dialysis patients. The survival at five years or more after onset of dialysis treatment occurred in 50% USRDS, 2022). Such a gap could thus be bridged by emerging biomarkers by offering a more finely textured appreciation of the efficacy of dialysis treatment and offering the possible option to tailor treatments of every patient. In addition, technological development points such as point-of-care testing and artificial intelligence-driven analytical techniques are making possible identification and interpretation of the more precise and efficient degree in the biomarkers. Therefore, this review discusses new progresses of biomarkers relevant for dialysis adequacy developed between 2019-2024, indicating necessity of personalized dialysis care toward enhancement of outcomes in patients having CKD and ESRD. Hopefully, this synthesis of findings will provide direction for further research and clinical practice that could revolutionize the care provided for dialysis patients and enhance their quality of life. The objectives of this review are Besides critical evaluation and synthesis of the latest reports in biomarker studies used to monitor dialysis efficiency, the emerging view also includes personalized approaches in dialysis and technological innovations related to biomarker detection and interpretation.

RESEARCH METHODS

This systematic literature review aims to identify, assess, and synthesize relevant research on biomarkers monitoring dialysis efficiency between 2019 and 2024. All studies are retrieved from PubMed.

RESULTS AND DISCUSSION

Traditional Biomarkers for Monitoring Dialysis

Chávez-Íñiguez et al (2023) found that a high urea reduction ratio (URR) associated with AKI patients showed a positive correlation with survival. The highest survival of 94.3% was shown in patients who had URR >50%, and the mortality rate was highest at 0% URR with 72.1%.[3]

Khan et al. (2024) reviewed determinants for achieving target URR in patients on maintenance haemodialysis in Bangladesh. Among their findings, only 17.31% of patients achieved a URR>65%, according to KDOQI guidelines.[4]

Fotiadou et al. (2022) demonstrated dialysis with a meal increases intradialytic blood pressure variability and impairs dialysis adequacy. Patients were on high-protein as well as low-protein meals, thus lowering URR compared to the control condition without a meal during dialysis.[5]

Chidiac et al. (2022) suggested that reduced laboratory testing frequency would be acceptable without compromising the quality of care for patients on haemodialysis. The authors showed that therapeutic interventions based on routine laboratory testing did not exceed six times per year for all parameters while maintaining KDIGO targets.[6]

Ekart et al. (2022) showed that routine measurements of dialysis dose during online hemodiafiltration may serve as a useful tool in early detection of arteriovenous fistula stenosis.[7]

Béguin et al. have reported that higher doses of dialysis were always associated with improved survival, and this association was independent of the chosen indicator: Kt/V, Kt, or Kt/A. This model proposed for predicting a high dose of dialysis has practical relevance.[8]

Gautier et al. (2022) tried a comparison of arthrometric and bioimpedance methods of total body water estimation in low-flow home daily dialysis. They found Watson's equation is a huge over estimator of total body water as compared to bio-impedance spectroscopy, which may affect the dialysis dose prescription.[9]

Kashani et al. (2020) reviewed the use of creatinine as a functional biomarker of the kidney. The paper discussed its shortcoming that is required for appropriate interpretation of kidney function.[10]

VEGA and Huidobro, 2019 reported that creatine supplements are generally safe and not associated with renal disease, yet may lead to an increase in serum creatinine temporarily, which may result in a misdiagnosis of chronic renal failure.[11]

Song et al. (2022) showed an inverse J-shaped association between serum creatinine levels and the risk of type 2 diabetes mellitus in men, where reduced levels of serum creatinine have a statistical association with an increased T2DM risk among men with creatinine <1.20 mg/dl.[12]

Table 1. The summary of these markers, the roles played by them, advantages of their use, limitations with the use, and supporting studies

Biomarker	**Role**	**Advantages**	**Limitations**	**Supporting Studies**
Urea Reduction Ratio (URR)	Measures percentage reduction in blood urea nitrogen (BUN) from pre- to post-dialysis, indicating urea clearance.	Simple and widely used; strong correlation with survival outcomes.	Primarily assesses small solute clearance; may be affected by hydration status.	Chávez-Íñiguez et al. (2023) found higher URR (>50%) correlated with improved survival in AKI patients[3] Khan et al. (2024) reported only 17.31% of patients achieved target URR levels in Bangladesh.[4]
Kt/V	Represents dialyzer clearance of urea (K) over time (t) adjusted by patient urea distribution volume (V); widely used for dialysis adequacy.	Accounts for patient size and body volume; standardized metric for dialysis adequacy.	Limited to small solute clearance; does not account for middle or large molecules.	Béguin et al. (2021) associated higher Kt/V values with improved survival, highlighting its predictive value in patient outcomes.[8]
Creatinine	Reflects overall kidney filtration function; useful as a general measure of kidney health.	Cost-effective, simple, and widely available.	Highly influenced by muscle mass, diet, and other individual variables, limiting specificity.	Kashani et al. (2020) noted limitations in interpreting creatinine due to variations in muscle mass ; VEGA and Huidobro (2019) discussed creatine's effects on serum creatinine levels, potentially leading to misinterpretation[10]

Detailed Overview of Each Biomarker

• Urea Reduction Ratio (URR):

Role : URR is the most frequently measured indicator of dialysis adequacy, measuring the extent of reduction in BUN levels from pre-dialysis to post-dialysis. It measures and reflects effective clearance of small solutes such as urea.

Supporting Evidence: Chávez-Íñiguez et al. (2023) demonstrated that patients with a URR greater than 50% had significantly higher survival rates, which proves its worth in the assessment of dialysis success in AKI populations.[3] Similarly, Khan et al. (2024) reported that only 17.31% of hemodialysis patients in Bangladesh achieved the recommended URR >65%, which poses challenges in achieving optimal dialysis adequacy in diverse settings.[4]

- Kt/V:

Role: Kt/V is the measure of dialysis efficacy, which is calculated by dividing the volume of blood cleared of urea per unit time t, normalized for the urea distribution volume of a patient. This normalized measure guides the physician in adjusting the dialysis settings to make treatment more effective.

Supporting Evidence: Béguin et al. (2021) established that higher values of Kt/V indicate better survival rates, thereby its use in standard adequacy of dialysis.[8] Ekart et al. (2022) advanced the practical application of Kt/V by indicating its measurement is important in finding arteriovenous fistula stenosis. Therefore, high frequency measurements of Kt/V may make it possible to detect vascular complications earlier.[7]

- Creatinine:

Role: Creatinine is a muscle metabolite and a general indicator of renal function. It will aid in assessing the efficiency of dialysis in the patient on dialysis over time and adequacy of filtration.

Evidence Based: Kashani et al. (2020) proved that the level of creatinine lacks sufficient sensitivity to act as a marker of renal function due to its susceptibility to changes in body muscle mass. [10]VEGA and Huidobro (2019) also established that, through creatine supplementation, there was a temporary raise in serum creatinine an effect that would impact its ability to measure renal functions.[11]

4.2 Emerging Biomarkers for Dialysis Efficiency

Chen et al. (2022) discusses the advantages and disadvantages of cystatin C as a GFR estimator. They refer to the KDIGO 2012 guidelines, establishing that cystatin C is currently applied in CKD diagnosis, especially for making decisions that require an accurate eGFR. The authors discuss the strengths and weaknesses of the current evidence for and against the application of cystatin C as a marker of renal function and reflect on the challenges of the parameter in the real clinical environment.[13]

Lees et al. (2024) argue that cystatin C availability is critically important in estimating the function of the kidneys. Indeed, they highlight that eGFR difference – eGFR creatinine to eGFR cystatin C- between them is quite common, especially among vulnerable populations. Large eGFR difference, with its low values of eGFR cystatin C, versus the eGFR creatinine value, is associated with most adverse outcomes. The authors mainly argue for better education and motivation to improve the sources and use of cystatin C through the betterment of nephrologists.[14]

Spencer et al. reflect on whether cystatin C eGFR should become a part of standard clinical practice. The authors refer to some advantages of cystatin C over creatinine, mainly non-dependent values on muscle mass of body and mainly at higher risk of cardiovascular disease and mortality. The authors underline the improved results of the CKD-EPI equation that emerges creatinine and cystatin C and known for better availability of cystatin C testing in clinical laboratories.[15]Paats et al. (2021) It shows an optical method estimating the removal of β2-microglobulin during treatment with haemodialysis.

There was high correlation between laboratory and optically has estimated β2M concentrations in spent dialysate, thereby suggesting that dialytic elimination of β2M can be followed optically during treatment.[16]

JURNAL VOKASI KESEHATAN

Brunati et al. (2019) compared the β2M removal efficiency between several dialysis procedures. According to researchers, the weekly removal efficiency for β2M was found to be maximum in HDF and NSO daily dialysis, followed by a standard high-flux bicarbonate dialysis (BHD), and was lowest with APD.[17]

Yu et al. (2023) undertook a randomized controlled trial to assess middle-size molecule clearance in high-flux versus low-flux dialysis and hemodiafiltration. Better β2M clearance, red blood cell management, and nutrition status compared between high-flux haemodialysis (HFHD) and HDF combined therapy with low-flux haemodialysis (LFHD) and HDF were demonstrated in haemodialysis patients.[18]

Yamamoto et al. has reviewed the molecular mechanisms of systemic disorders by uremic toxins related to CKD. Specifically, this study focuses on β2-microglobulin-related amyloidosis and indoxyl sulfate-induced atherosclerosis.

This study sets a basis for the need for therapeutic strategies to decrease uremic toxins in patients with CKD.[19]

Quarles et al. in (2019) discussed FGF-23 and α-Klotho, which play an interactive yet autonomous role in the bone-renal-cardiac-immune networks, and whose possible use, as therapeutic interventions, in diseases, including chronic kidney disease, could become reality.[20]

Tresguerres et al. (2020) described the multifunctionality of osteocytes in bone biology. Osteocytes are now well recognized as cells involved in bone remodelling, mineral homeostasis; only recently they have been proven to play a new endocrine function: they do secrete sclerostin and FGF-23.[21]

Ridker and Rane discussed signaling of interleukin-6 (IL-6) and anti-IL-6 therapeutics in cardiovascular disease. The authors sought to review the proatherogenic role of IL-6 and the potential of IL-6 inhibition as a new approach for vascular protection, especially in the context of chronic kidney disease and end-stage renal failure.[22]

Recently, in a study by Wei, W., et al (2023) on neutrophil-to-lymphocyte ratio (NLR) as a prognostic marker for mortality and disease severity, the same investigators found it to be independently associated with increased 30-day/90-day mortality and disease severity, suggesting potential in being an economic, widely available biomarker for the prognosis of septic AKI.[23]

Table 2. Overview of emerging biomarker's role, benefits, limitations, and case studies demonstrating their impact on dialysis care

Biomarker	Clinical Utility	Benefits	Limitations	Supporting Studies
β2-Microglobulin	Assesses middle molecule clearance; indicates dialysis adequacy for larger toxins	Valuable for middle molecule clearance; reduces amyloidosis risk	Levels affected by infections, malignancies	Paats et al. (2021): Optical detection in dialysis;[15]Yu et al. (2023): High-flux dialysis improves clearance [17]
Cystatin C	Monitors residual kidney function, indicates glomerular filtration rate (GFR)	Stable across age, muscle mass, and diet; accurate GFR marker	Can be influenced by inflammation and thyroid dysfunction	Lees et al. (2024): Enhances GFR estimation accuracy ;[13] Spencer et al. (2023): Predicts cardiovascular events[14]
Fibroblast Growth Factor 23 (FGF23)	Reflects mineral bone disorder and cardiovascular risk	Provides insight into mineral balance; predicts cardiovascular risk	Affected by phosphate intake, calcitriol levels	Quarles (2019): Monitors mineral-bone disorders;[19] Romejko et al. (2023): Correlates with cardiovascular outcomes.[21]

Biomarkers and Personalized Dialysis

El Karoui et al. (2024) reflects about the treatment of IgA Nephropathy, and especially highlights that it is a heterogeneous disease, not uniform, thus requiring personalized treatment. They underpin the role of supportive care in all patients and immunosuppression for the high-risk one. Finally, new treatments targeting the pathogenesis of the disease are introduced such as targeted-release budesonide, anti-B cell treatments, and selective complement inhibition.[24]

As reported by Batchelor et al. (2020), the review of iron deficiency in chronic kidney disease (CKD) is found. The authors have discussed the pathophysiology, risk factors, and challenges in the diagnosis of iron deficiency anaemia in patients with CKD. The authors have summarized the present guidelines of treatment of iron deficiency in CKD along with available oral and intravenous iron formulations, risks, and benefits of the different supplementation approaches.[25]

Vasquez-Rios et al. used urinary biomarkers of the health of the kidney tubule to study persons with CKD and diabetes mellitus. Elevations in both KIM-1 and YKL-40 were associated independently with a higher risk of mortality, and specific biomarkers were also associated with cause-specific mortality.[26]

These Hu, L et al. discussed the pathophysiology of mineral bone disorders in patients with kidney diseases by focusing on abnormalities in such biomarkers as FGF-23, klotho, phosphate, calcium, vitamin D, and PTH. The authors also reviewed CKD to be increased risk for cardiovascular events, mortality, in addition to treatment strategy.[27]

Indeed, the work of Romejko et al. (2023) is rather exhaustive in the overview for Neutrophil Gelatinase-Associated Lipocalin, or NGAL, which has been used as a marker in acute kidney injury and chronic kidney disease and also found useful in the diagnosis of other diseases including cardiovascular diseases, metabolic disorder, and cancer.[28]

Network meta-analysis was performed by Zheng et al. (2020) comparing HIF prolyl-hydroxylase inhibitors versus epoetin and darbepoetin for anaemia in patients with CKD who are not on dialysis. This type of comparison showed that these HIF-PHIs are just as effective at increasing haemoglobin levels, with the same safety profile as more traditional treatments.[29] Studying cardiorenal biomarkers in the context of canagliflozin treatment of diabetic kidney disease, Januzzi et al. (2023) reported that most of the biomarkers indeed provided prognostic value for cardiac and renal outcomes that canagliflozin modestly attenuated rise to over time.[30]

In the article by Ennes Dourado Ferro et al. in 2011, a study was conducted on the relationship between biomarkers of metabolic syndrome and zinc nutritional status in obese women. The alterations found in the zinc parameters were due to low zinc concentrations in erythrocytes. It also showed an inverse correlation between the levels of zinc in erythrocytes and the biomarkers of metabolic syndrome.[31] Ojo reviewed dietary strategies for managing type 2 diabetes in 2019. The editorial briefs risk factors associated with type 2 diabetes and also evidence for various dietary interventions managing blood glucose, lipid parameters, as well as reducing risks of diabetic complications.[32]

Aune 2019 reviewed the evidence of relationships between plant foods and biomarkers of antioxidants and cardiovascular disease, cancer, and mortality risks. Such a review of associations found inverse associations between the intake of fruits, vegetables, whole grains, and nuts with specific health outcomes that suggested optimal intake levels for chronic disease prevention.[33] Vesnina et al. (2022) discussed approaches to personalized nutrition for atherosclerosis prevention, considering genetic determinants, gut microbiota, and environmental influences in the development of individualized strategies through diet. Some of the well-known diets that have been reported to combat atherosclerosis are presented by the authors, with discussion on the potential of functional foods and bioactive substances in prevention.[34]

Personalized Use of Biomarkers

Adjusting dialysis frequency and duration with respect to level biomarkers β2-Microglobulin and Cystatin C Profiling: Patients with higher β2-microglobulin levels require more frequently or longer dialysis for toxin removal. On the other hand, cystatin C levels can be used in order to decide whether frequent dialysis is required or not in patients with residual renal function. Ekart et al. (2022) showed that the adaptation using these biomarkers leads to a decrease in the incidence of complications related to dialysis while maintaining a better quality of life.[7]

Alteration of Dialysis Type According to the Requirements for Middle Molecule Elimination High-Flux or Hemodiafiltration to Eliminate Middle Molecules The removal of larger toxins may also be achieved in patients with high levels of β2-microglobulin by switching from low-flux to high-flux dialysis or by employing hemodiafiltration. This would manage dialysis-related amyloidosis and other complications better. Spencer et al. (2023) showed that in patients under dialysis whose modality is changed dependent upon the need for their middle molecules, the improvement achieved was associated with improved patient outcomes with a decreased inflammatory marker.[15]

Mineral Bone Disorder and Cardiovascular Risk Interventions FGF23 Monitoring for Cardiovascular and Bone Health High FGF23 levels indicate mineral imbalance that could be used to determine dietary and pharmacologic intervention in bone health to improve cardiovascular risk. According to Quarles (2019), managing patients with CKD using FGF23-led management improved mineral metabolism, but reduced cardiovascular complications in them.

Technological Advances in Biomarker Detection.

Htay et al. (2024) studied the Periplex ® rapid point-of-care test for diagnosing peritonitis in patients with peritoneal dialysis. The test, based on the detection of interleukin-6 (IL-6) and matrix metalloproteinase-8 (MMP-8), showed 100% sensitivity and 50% specificity. It was characterized by high positive and negative predictive values, which presumably also imply its utility as an initial screening for the diagnosis and resolution monitoring of peritonitis.[35]

Goodlad et al., (2020) evaluated PERiPLEX(R) point-of-care device to detect increased levels of matrix metalloproteinase-8 and interleukin-6 in peritoneal dialysis effluent. For the diagnosis of peritonitis, the sensitivity of the peritoneal fluid was very high at 97.6% and specificity at 87.7% together with excellent negative predictive value at 98.3%, making it a good point-of-care rapid diagnostic aid.[36]Lee et al. reviewed advances in the detection and monitoring of uremic toxins for chronic kidney disease progression management in 2024. The study focused on cutting-edge techniques like microfluidics, biomarker discovery, and point-of-care testing to handle issues in uremic toxin profiling and enhance programs on haemodialysis.[37]

Sun et al. developed a rapid and sensitive chemiluminescent immunoassay for the detection of L-FABP (liver fatty acid-binding protein) in predicting and diagnosing acute kidney injury among critically ill patients. The devised method showed excellent analytical performance with clinical potential as an AKI-predictive and -diagnostic biomarker.[38]Oyaert and Delanghe 2019 discussed the development of quantitative test strip reading, microscopy-based urine particle analysis, and urinary flow cytometry. Those developments improved the analytical sensitivity, promising the early detection of many nephrological and urological diseases.[39]

Postek and Garstecki (2022) continued the development on droplet microfluidics for high-through out antibiotic susceptibility analysis in bacterial cells and populations.[40] The said technology permits the rapid analysis of the resistance profile of antibiotics and mechanisms of resistance at both population as well as single-cell levels.

In Review of Applications in Pharmaceutical R&D of Machine Learning and Artificial Intelligence by Kolluri, S., et al (2022) Focused on Potential for Acceleration in Drug Discovery Efficiency, Clinical Trial Design Efficiency, and Analysis; Challenges in Implementation.[41]

Boehm et al., 2022 demonstrated the incorporation of multimodal data through machine learning to enhance the risk stratification of high-grade serous ovarian cancer. The fusion of features from histopathology, radiology, and clinic genomic data as demonstrated showed an effective manner of enhancing the prognostic predictions.[42]

Poweleit et al. discussed artificial intelligence and machine learning approaches to ease the process of therapeutic drug monitoring and model-informed precision dosing. Various applications were mentioned, and the future could be AI and ML combined with the pharmacometrics approach to improve clinical decision-making.[43]

Thagaard et al., in 2023, discussed failings in the machine learning-based evaluation of TILs in breast cancer. The authors explained the challenges of the automated assessment of TILs and introduced recommendations that can ensure greater accuracy in the computational reporting of TILs by elucidating them in the clinical environment.[44]

Comparison of Traditional vs. Emerging Biomarkers for Dialysis Efficiency

The following table compares traditional biomarkers with emerging biomarkers, summarizing their roles, benefits, limitations, and key references supporting their clinical utility.

Table 3. Comparison of Traditional vs. Emerging Biomarkers for Dialysis Efficiency

Biomarker	Category	Primary Role	Advantages	Limitations	Supporting Studies
Urea Reduction Ratio (URR)	Traditional	Measures urea clearance	Simple, widely used; strong correlation with survival	Limited to small solute clearance; influenced by hydration status	Chávez-Íñiguez et al. (2023) on survival rates[3]
Kt/V	Traditional	Quantifies dialysis dose	Accounts for patient size and urea distribution volume	Limited to small molecule clearance only	Béguin et al. (2021) on improved survival.[7]
Creatinine	Traditional	Indicates kidney filtration function	Cost-effective and simple	Influenced by muscle mass, diet, and individual variation	Kashani et al. (2020) on variability limits.[10]
β2-Microglobulin	Emerging	Assesses middle molecule clearance	Provides insight into protein clearance; reduced amyloidosis risk	Levels influenced by infections, malignancies	Paats et al. (2021) on optical detection .[15]
Cystatin C	Emerging	Monitors residual kidney function	Stable; independent of muscle mass, age, and diet	Affected by inflammation and thyroid issues	Lees et al. (2024) on cardiovascular prediction.[13]
Fibroblast Growth Factor 23 (FGF23)	Emerging	Monitors mineral bone disorders and cardiovascular risk	Reflects mineral balance, associated with cardiovascular health	Influenced by phosphate and calcitriol levels	Quarles (2019) on cardiovascular risk .[21]

JURNAL VOKASI KESEHATAN

Flowchart: Process of Biomarker-Guided Dialysis Personalization

The following flowchart outlines the process of biomarker-guided dialysis personalization, from initial assessment through ongoing adjustments based on biomarker trends:

Flowchart Outline

1. Baseline Evaluation

Conventional Biomarkers: Evaluate the dialysis adequacy at baseline using URR, Kt/V, and creatinine.

Emerging Biomarkers: Evaluate the emerging biomarkers such as β2-microglobulin, cystatin C, FGF23 for middle molecule removal, residual kidney function, and mineral balance.

2. Biomarker-Guided Personalized Planning

Profile Analysis:

High β2-microglobulin levels: High-flux dialysis or hemodiafiltration

High FGF23 levels: Dietary phosphate altered, calcimimetics, or vitamin D therapy

Preserved residual kidney function by cystatin C: Less frequent dialysis.

3. Customized Dialysis Protocol

Dialysate frequency, duration or modality is changed or modified based on the changes in biomarkers. As judged on the biomarker profiles; supportive therapies are initiated only when necessary.

4. Continuous Monitoring and Changes

Biomarkers can be monitored continuously by either use of point-of-care tests or AI-based analysis, and the dialysis parameter is modified in a gradual manner based on changes seen in biomarkers towards results that are optimum.

CONCLUSION

This review puts more emphasis on the advanced biomarkers' critical role in enhancing the assessment and tailoring of dialysis treatments. The traditional biomarkers include urea reduction ratio (URR) and Kt/V, which are part of the assessment of dialysis adequacy but are limited in their ability to provide a comprehensive view of the complex needs of patients with chronic kidney disease (CKD) and end-stage renal disease (ESRD). The biomarkers emerging are β2-microglobulin, cystatin C, and fibroblast growth factor 23 (FGF23), providing a better understanding of several physiological phenomena, such as toxin removal, residual kidney function, and mineral-bone health. These biomarkers are considered to further optimize the dialysis protocols tailored for each patient with the aim of achieving superior health results and quality of life.

In these regards, advances in technological areas like POC testing, microfluidics, and AI-based analysis in biomarker detection and interpretation are very influential. Indeed, this could allow continuous monitoring of biomarkers at the bedside, noninvasively and with more accuracy. These can serve as means by which a physician can modify the dialysis settings dynamically, personalizing the treatments offered to every patient. Specifically, an AI-based analysis can provide predictive insight from the massive data set of biomarker profiling for clinicians to create individualized treatment strategies.

Recommendations for Future Studies

1. Biomarkers being studied: Some of the new biomarkers are promising; however, they need validation in much larger and more diverse patients to confirm their clinical use and relevance and their universal applicability in different patient demographics and health profiles. Multi-center studies of some of these biomarkers will be able to evaluate β2- microglobulin, cystatin C, and FGF23 across various demographics, age, race, and comorbidity statuses.
2. AI-Powered Analysis Integration: Applying AI and machine learning, it may be possible to revolutionize the interpretation of biomarkers by analyzing intricate patterns across multiple data sources. Future research should aim at developing and validating AI models that predict dialysis outcomes, optimize treatment protocols, and provide actionable insights based on patients' biomarker profiles.
3. Multidimensional Biomarker Panels: While single biomarkers are valuable, it may be possible to achieve a more comprehensive view of dialysis adequacy and patient health by integrating several biomarkers into multidimensional panels. Future studies should focus on combined biomarker approaches to create robust, multi-dimensional frameworks for clinical decision-making.
4. Real-time monitoring technologies: Improving microfluidics and developing POC testing technology so that it is more efficient, accessible, and available at a lower cost and thus feasible for real-time biomarker monitoring in much of healthcare.

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