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REVIEW

Advanced Echocardiographic Approaches for Assessing Cardiac Dysfunction in Chronic Kidney Disease: Current Techniques and Future Perspectives

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Abstract: The incidence of chronic kidney disease (CKD) has been consistently rising in recent years. This trend is particularly concerning in the aging population, where the prevalence of CKD and cardiovascular disease is disproportionately high. Among CKD patients, cardiovascular disease stands as the primary prognostic risk factor and leading cause of mortality. Early cardiac function assessment is critical, especially in older adults, for diagnosis and treatment guidance due to their atypical presentations and high risk. Due to its convenience, lack of radiation, and excellent repeatability, ultrasound has become a widely used method for evaluating cardiac function. Furthermore, with the rapid advancements in medical technology, numerous innovative ultrasound techniques have been introduced for assessing cardiac function.

Keywords: chronic kidney disease, cardiorenal syndrome, echocardiography, cardiac function, advanced ultrasound techniques

Introduction

Chronic kidney disease (CKD), affecting approximately 15–20% of the global adult population, significantly increases the risk of cardiovascular disease (CVD), which remains the primary cause of mortality in this patient demographic.[1–3] Given the substantial burden of CVD in CKD, early and precise non-invasive assessment of cardiac structure and function is critical for guiding therapeutic strategies and improving prognosis.

The interplay between renal and cardiac dysfunction, often termed cardiorenal interaction, is particularly complex in elderly CKD patients due to comorbidities like frailty and polypharmacy, further complicating clinical management.[4] In CKD, this interplay disproportionately drives cardiovascular complications, which are the leading cause of morbidity and mortality. Key among these is "uremic cardiomyopathy" (UC), a pathological remodeling of the heart commonly observed in CKD patients, characterized by structural and functional cardiac abnormalities.[5] The pathophysiology of UC is multifaceted, encompassing both traditional cardiovascular risk factors (eg, hypertension, volume overload) and CKD-specific factors such as uremic toxins, systemic inflammation, oxidative stress, and mineral and bone disorders. These factors collectively promote distinct pathological changes in the myocardium, including myocardial hypertrophy (both concentric and eccentric), diffuse interstitial fibrosis, and impaired myocardial relaxation.[6] In elderly CKD patients, these changes are often compounded by age-related cardiac remodeling, making the recognition and characterization of UC particularly challenging. The morphological and functional myocardial changes associated with cardiorenal interactions are highly amenable to assessment by echocardiography.[7,8] For instance, left ventricular hypertrophy is a common and prognostically significant finding, while myocardial fibrosis, though directly assessed by advanced imaging like

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magnetic resonance imaging (MRI), contributes to echocardiographic findings such as diastolic dysfunction and impaired myocardial strain.[9]

Echocardiography stands as a cornerstone in this assessment due to its non-invasiveness, absence of radiation, cost-effectiveness, and real-time imaging capabilities. Recent advancements in ultrasound technology have significantly expanded its diagnostic utility, allowing for more detailed characterization of cardiac abnormalities beyond traditional parameters.[8–10] This comprehensive literature review aims to: 1) summarize the advanced echocardiographic techniques available for assessing cardiac function in CKD patients; 2) discuss the unique considerations and challenges for echocardiographic assessment in elderly CKD patients, including the impact of age-related cardiac changes and frailty; and 3) highlight the prognostic value of advanced echocardiographic parameters in this vulnerable population.

To provide a comprehensive overview of cardiac dysfunction screening with ultrasound in patients with CKD, a focused literature search was conducted across several prominent electronic databases. These included PubMed and Web of Science. The search encompassed articles published from database inception up to April 2025, ensuring a broad coverage of the existing literature. Boolean operators were employed to combine key search terms. The primary keywords and phrases utilized were: ("chronic kidney disease" OR "CKD" OR "renal failure") AND ("cardiac dysfunction" OR "heart failure" OR "cardiovascular disease") AND ("ultrasound" OR "echocardiography") AND ("screening" OR "assessment" OR "evaluation" OR "technique"). Relevant articles, including original research, review articles, and clinical guidelines, were then identified and selected based on their direct relevance to the review's objectives. Emphasis was placed on studies discussing the application of various ultrasound techniques for cardiac assessment in CKD patients, particularly those highlighting novel approaches or clinical implications. In addition, a comprehensive summary table (Table 1) has been included to synthesize the key echocardiographic studies discussed, outlining study populations, methodologies, main findings, and limitations.

Conventional Echocardiography

Standard two-dimensional echocardiography provides information on the anatomy of cardiac valves, left ventricular mass, endocavitary volume, left ventricular geometry, atrial volume and the pericardium. Tissue Doppler imaging (TDI) adds information regarding heart structure and function; for example, ventricular systole and relaxation, myocardial performance, transvalvular velocities and cardiac chamber filling pressure.[23] As previously mentioned, UC primarily manifests as myocardial fibrosis, left ventricular hypertrophy, and diastolic and/or systolic dysfunction. Two-dimensional echocardiography provides a comprehensive depiction of cardiac morphology, ventricular wall thickness, and motion dynamics.

A large-scale single-center cohort study examined myocardial diastolic dysfunction in CKD patients through comprehensive echocardiographic examinations of 20,257 adult patients (mean age 62.2 ± 16.2 years). The study revealed that diastolic dysfunction of the left ventricle precedes a decrease in the ejection fraction.[24] Early detection of diastolic dysfunction is therefore beneficial for timely diagnosis and treatment. Several conventional echocardiographic techniques are available to evaluate left ventricular diastolic function, including pulsed wave, continuous wave, and TDI. These techniques provide a comprehensive set of parameters crucial for assessing diastolic dysfunction. Key parameters include the mitral inflow E/A ratio, early diastolic mitral annular velocity (e'), and the mitral E/e' ratio, which is widely used to estimate left ventricular filling pressures.[25] Beyond these, other crucial indicators, frequently recommended by guidelines for a more complete assessment of diastolic function, are also routinely measured. These include the peak tricuspid regurgitation velocity (TRV), which is valuable for estimating pulmonary artery systolic pressure and inferring left atrial pressure, and the left atrial maximum volume index (LAVI) obtained through two-dimensional measurements.[25] A study assessed the E/e' ratio in patients with CKD stages G3 to G5 (mean age 61.13 ± 12.91 years) and conducted a longitudinal follow-up over five years, concluding that the E/e' ratio is a predictive marker for mortality and cardiovascular events in patients with diastolic dysfunction secondary to CKD.[11] Another investigation focused on CKD patients at stages G3 and G4, who had no prior history of heart disease. These patients (mean age 62.8 ± 10.6 years) underwent echocardiographic evaluations both at rest and during exercise to determine the exercise-induced E/e' ratio. Following a five-year follow-up period for major adverse cardiovascular events, the study identified that an elevated exercise E/e' ratio in patients with CKD serves as an independent predictor of such events.[12] Consequently, it is

Table 1 Summary of Key Echocardiographic Studies Mentioned in the Article

Research Technique/ Parameter	Study Population	Research Methodology	Key Findings	Limitations	Ref.
E/e'	CKD G3-G5 patients (n=136, mean age 61.13 ± 12.91 yrs)	Longitudinal follow-up (5 years), assessment of resting E/e'	E/e' is a predictive marker for mortality and cardiovascular events in patients with diastolic dysfunction secondary to CKD	Limited to CKD G3-G5 patients with diastolic dysfunction; observational studies may have unadjusted confounding biases	[11]
Exercise E/e'	CKD G3-G4 patients (n=156, mean age 62.8 ± 10.6 yrs), without a history of heart disease	Resting and exercise echocardiography assessment, 5-year follow-up for MACE	Elevated exercise E/e' is an independent predictor of MACE in CKD patients	Applicable to G3-G4 CKD patients without a history of heart disease; exercise testing may have limitations in some CKD patients (eg, frailty)	[12]
LAVI	CKD G1-G5 patients (n=213)	Assessed the relationship between LAVI and the occurrence of heart failure, measuring its correlation with biomarkers; median follow-up of 16 months	LAVI is significantly associated with the occurrence of heart failure, positively correlated with NT-proBNP and CK-MB, and has independent predictive value	Moderate sample size and follow-up duration; conclusions depend on the accuracy of LAVI measurement	[13]
LVEF, pulmonary artery pressure, right ventricular diameter	Adult patients with at least one transthoracic echocardiography (n=30,681, mean age 68 ± 14 yrs)	Assessed the relationship between LVEF, pulmonary artery pressure, right ventricular diameter and the incidence of CRS	Reduced LVEF, elevated pulmonary artery pressure, and increased right ventricular diameter are independently associated with a higher incidence of CRS	Retrospective cohort study, potential for bias in data collection	[14]
LVMI, LVEF, LV Geometry	CKD patients (n=3505)	Assessed the relationship between baseline parameters and the incidence of heart failure and mortality	LVMI, LVEF, LV geometric structures are independently associated with increased risk of subsequent heart failure incidence and mortality in CKD patients	Observational study, conclusions depend on accurate measurement of parameters	[15]
2D-STE (GLS)	Pre-dialysis and dialysis patients with CKD stage 3b-5, with normal LVEF (n=200, mean age 60 ± 14 yrs)	Observational study, evaluated GLS, followed up on heart failure hospitalization and all-cause mortality	Even with normal LVEF, GLS impairment exists. Patients with impaired GLS and normal LVEF have an increased risk of heart failure hospitalization and all-cause mortality	Applicable to dialysis and non-dialysis CKD patients with normal LVEF, emphasizing subclinical impairment; technology-dependent limitations of STE	[16]
2D-STE (GLS vs LVEF)	Patients with CKD stage 4, 5 and 5Dialysis (n=183)	Prospective study, follow-up duration 7.8 ± 4.4 years, evaluated predictive ability of GLS and LVEF	GLS has better predictive ability for all-cause mortality and cardiovascular mortality than LVEF	Moderate sample size, long follow-up period, high credibility; applicable to dialysis and non-dialysis CKD patients; high proportion of death events (61%), possibly reflecting a high-risk population	[17]
3D-STE (GLS, LVMI)	MHD patients (n=66)	Evaluated subclinical left ventricular changes and cardiovascular events	GLS and LVMI are important predictors of cardiovascular events in MHD patients	Small sample size, limited to MHD patients; 3D-STE has high image quality requirements and is unsuitable for arrhythmias; analysis algorithms vary significantly	[18]
Layered Strain	Uremic patients (n=119)	Evaluated layered strain, compared LS and CS in each layer	Subendocardial function was impaired even without LVH	Technical limitations: high image quality and frame rate requirements, myocardial layer interdependence, operator experience has a large impact	[19]
Myocardial Work	MHD patients (n=68)	Evaluated myocardial work parameters (GWI, GCW, GWW, GWE) to analyze left ventricular systolic function	Myocardial work parameters demonstrated significant AUC, sensitivity, and specificity in assessing left ventricular function in MHD patients	Focused on methodological validation; technical limitations: brachial artery pressure as a surrogate for left ventricular intra-cavitary pressure, which may be inaccurate in patients with abnormal blood pressure or vascular lesions	[20]
DSE (compared with (myocardial perfusion scintigraphy)	Renal transplant candidates (n=690, meta-analysis of 11 studies)	Meta-analysis comparing DSE and myocardial perfusion scintigraphy	DSE has high sensitivity and specificity for detecting coronary artery stenosis, better than myocardial perfusion scintigraphy	Only suitable for renal transplant candidates	[21]
DSE (degree of ischemia from DSE)	CKD patients (n=485, mean age 61 ± 14 yrs)	Assessed the relationship between DSE-detected ischemia extent and all-cause mortality	DSE-detected ischemia extent is an independent predictor of all-cause mortality; patients with extensive ischemia have lower 1-year and 3-year survival rates	Observational study, cannot establish a causal relationship	[22]

evident that the E/e' ratio, a straightforward and easily obtainable parameter of diastolic function, possesses substantial clinical utility in prognosticating cardiovascular outcomes in CKD patients. Nonetheless, the assessment of exercise E/e' may present technical difficulties, especially in CKD patients who also suffer from frailty and exercise limitations. LAVI is a fundamental measure reflecting the chronicity and severity of elevated left ventricular filling pressures, while TRV provides an estimation of pulmonary artery systolic pressure, indirectly reflecting left atrial pressure. Both LAVI and TRV are vital for a holistic characterization of diastolic dysfunction. In one study, LAVI was used to assess left atrial function in patients with CKD, revealing a significant association with the occurrence of heart failure. The study indicated that LAVI is positively correlated with cardiac biomarkers such as NT-proBNP and CK-MB, and possesses independent predictive value in heart failure prediction.[13] Furthermore, increased LAVI is associated with increased cardiovascular mortality and morbidity in CKD patients, further emphasizing its importance in clinical assessment.[26] On the other hand, an increased TRV may reflect changes in right ventricular function and is related to changes in left atrial pressure.[27] In practical clinical settings, a comprehensive consideration of various indicators is essential when assessing diastolic function. Selecting parameters that are operationally feasible, reproducible, and of high image quality can enhance diagnostic accuracy.

Conventional ultrasound parameters for assessing left ventricular systolic function include the left ventricular ejection fraction (LVEF), mitral annular plane systolic excursion (MAPSE), and mitral annular systolic peak velocity (S'). Similar to the general population, echocardiography is recommended to detect systolic functional alterations of the heart in patients with CKD or kidney failure. This technique is also mandatory for identifying heart failure subtypes (reduced EF, mildly reduced EF and preserved EF) in patients with CKD.[9,28] LVEF can be measured by M-mode ultrasound or the biplane Simpson method, with the latter providing greater accuracy in altered left ventricular morphology or presence of segmental wall motion abnormalities. A retrospective cohort study involving 30,681 patients (mean age 68 ± 14 years) found that reduced LVEF, increased pulmonary artery pressure, and enlarged right ventricular diameter are independently associated with a high incidence of cardiorenal syndrome (CRS).[14] Additionally, baseline conventional echocardiographic parameters (LV mass index, LVEF, and LV geometry) are independently associated with increased risk of subsequent heart failure morbidity and mortality in CKD patients.[15] MAPSE and mitral annular S' are simple and reproducible parameters widely used in clinical practice, however, it is crucial to recognize that both MAPSE and mitral annular S' are angle-dependent and can be influenced by ventricular loading conditions, which may limit their accuracy in certain clinical scenarios. Especially in elderly patients, the presence of myocardial fibrosis and calcification might further complicate the interpretation of these parameters by altering myocardial mechanics.[29]

UC not only affects the left heart but also frequently affects the right heart. Even in the early stages of the disease when LVEF is normal, right ventricular systolic dysfunction may be present.[30] Conventional ultrasound parameters for assessing right ventricular systolic function include right ventricular fractional area change, tricuspid annular plane systolic excursion (TAPSE), and tricuspid annular systolic peak velocity (S'). TAPSE and tricuspid S' are not influenced by right ventricular geometry, are easy to measure, and exhibit high reproducibility despite their angle dependency.[31,32] TAPSE, a parameter for right ventricular systolic function, has been shown to be a strong predictor of acute CRS development in patients with inferior acute myocardial infarction.[33]

Speckle Tracking Echocardiography (STE)

STE is an advancing technology for assessing cardiac function, encompassing two-dimensional speckle tracking echocardiography (2D-STE) and three-dimensional speckle tracking echocardiography (3D-STE). 2D-STE utilizes computer software to automatically identify myocardial speckle signals and obtain strain information for myocardial segments. 3D-STE, built upon 2D-STE, tracks myocardial speckles in three-dimensional space, enabling precise evaluation of global and segmental cardiac function.[34] Compared to conventional echocardiography, STE offers more accurate assessments of systolic function by evaluating cardiac deformation.[35–37] An observational study demonstrated that global longitudinal strain (GLS) measured by 2D-STE can quantitatively evaluate global and segmental systolic function in CKD-related cardiomyopathy patients.[38] Another study involving predialysis and dialysis patients (mean age 60 ± 14 years) revealed that even with normal LVEF, GLS impairment was present, and patients with impaired GLS and normal LVEF had an increased risk of heart failure hospitalization and all-cause mortality.[16] Similarly, GLS measured by

2D-STE independently associated with increased risk of all-cause mortality and cardiovascular mortality in CKD patients. A prospective study enrolled 183 CKD patients, both dialysis and nondialysis, utilized 2D-STE to measure GLS and the Simpson biplane method to measure LVEF. Among these patients, 112 (61%) died during a follow-up period of 7.8 ± 4.4 years, with 41% of the deaths attributable to CVD. The analysis concluded that GLS had superior predictive abilities for all-cause mortality and cardiovascular mortality compared to LVEF.[17] Another study sumarised that GLS predicted all-cause and cardiovascular mortality in patients with stage G3-4 CKD (mean age 71 ± 11 years).[39]

Additionally, Sun et al employed 3D-STE to evaluate subclinical left ventricular alterations in patients undergoing maintenance hemodialysis (MHD) and to monitor subsequent cardiovascular events.[18] Their findings indicated that GLS and left ventricular mass index serve as significant predictors of cardiovascular events in this patient population. The assessment of strain in these individuals may facilitate cardiovascular risk stratification. Nonetheless, 3D-STE is subject to certain limitations: it necessitates high-quality imaging, is inapplicable to patients with arrhythmias such as atrial fibrillation, and exhibits considerable variability in analysis algorithms among different manufacturers. Therefore, measurements derived from 3D-STE should be interpreted within the specific context of the acquisition platform and the analytical software employed.

Given that the application of STE requires high image quality and relies on the clarity of the endocardium, its use is limited in some CKD patients with poor cardiac imaging quality. Tissue motion annular displacement (TMAD), an emerging technique based on 2D-STE, demonstrates potential in the evaluation of left ventricular systolic function. Numerous studies have indicated that TMAD parameters exhibit strong correlations with LVEF and GLS, moreover, this technique is simple, quick, and has good reproducibility, while also requiring lower image quality standards, thereby serving as a sensitive indicator for the assessment of left ventricular systolic function.[40,41]

STE can be used not only to assess ventricular function but also to evaluate atrial function. Normal atrial function includes reservoir function during ventricular systole, conduit function during early ventricular diastole, and booster pump function during late ventricular diastole, all of which contribute to left ventricular filling and cardiac output.[42,43] Atrial remodeling in CKD patients is characterized by atrial enlargement and fibrosis, leading to increased left atrial volume and decreased left atrial EF. 2D-STE can track the motion of atrial speckles, quantitatively evaluating left atrial phasic function and providing measurements of left atrial reservoir strain, conduit strain, and contraction strain, which is valuable for assessing left ventricular diastolic dysfunction.[44,45] In a study that used STE in patients on haemodialysis or peritoneal dialysis, 50% of participants (mean age 62.3 ± 11.8 years) showed impaired left atrial strain.[46] Studies also have shown that left atrial strain parameters have the potential to estimate left ventricular end-diastolic pressure and are correlated with exercise capacity and have predictive value for major adverse cardiovascular events in CKD patients.[47–49] In addition to LVEF, the conduit phase of left atrial strain was significantly associated with a combined end point, including all-cause and cardiovascular mortality, myocardial infarction and hospitalizations due to cardiac adverse events.[46] Therefore, 2D-STE measurements of left atrial strain parameters can be utilized to assess left ventricular diastolic function and predict major adverse cardiovascular events in end-stage renal disease patients.

Layered Strain Technology

Layered strain represents an innovative technique recently developed, predicated on 2D-STE. This method entails segmenting the left ventricular myocardium into three distinct layers: endocardial, mid-myocardial, and epicardial. By tracking the speckle signals within each layer, the technique derives motion parameters in multiple directions, facilitating a precise evaluation of both global left ventricular function and the functional dynamics of each myocardial layer.[50] Several researchers have utilized layered strain analysis to evaluate the longitudinal and circumferential contraction functions of the myocardium and its individual layers in patients with uremia.[19] They stratified 119 uremic patients into two groups: those with normal left ventricular function and those with left ventricular hypertrophy, based on the presence of left ventricular hypertrophy. The results indicated that, among the three myocardial layers, the subendocardial longitudinal strain (LS) and circumferential strain (CS) were the highest, whereas the subepicardial LS and CS were the lowest. Furthermore, in comparison to the normal control group, the left ventricular normal group demonstrated a significant reduction in LS, suggesting that subendocardial function is compromised even prior to the onset of left ventricular hypertrophy. Consequently, layered strain analysis can detect early alterations in LS and CS in patients undergoing MHD, thereby serving as a diagnostic tool for left ventricular systolic dysfunction. Furthermore, layered strain analysis has the capability to identify changes in specific myocardial layers or segments before global myocardial strain alterations become evident. However, the limitations of layered strain technology encompass stringent requirements for image quality and frame rate, as well as the interdependence of the three myocardial layers, which can affect the accuracy of the analysis. On the other hand, similarly to STE, operator experience significantly influences the accuracy and reproducibility of layered strain. Experienced operators are more adept at optimal image acquisition, avoiding artifacts, and accurate placement of regions of interest, which reduces variability. Ensuring consistent training programs and ongoing quality control are essential to minimize operator-dependent variability and enhance the reliability of these sophisticated assessments in clinical practice.

Non-Invasive Myocardial Work

Non-invasive myocardial work integrates non-invasive dynamic left ventricular pressure with strain parameters obtained through 2D-STE to construct a left ventricular pressure-strain loop. This methodology accounts for both myocardial deformation and afterload, thereby emerging as a novel and more sensitive indicator for detecting subclinical myocardial dysfunction. The parameters of myocardial work include the Global Work Index (GWI), Global Constructive Work (GCW), Global Wasted Work (GWW), and Global Work Efficiency (GWE).[51] Studies have substantiated that myocardial work indices, as assessed by non-invasive left ventricular pressure-strain loops, exhibit strong consistency and correlation with those obtained through invasive methods.[52,53] Liu et al employed myocardial work to evaluate left ventricular systolic function in patients undergoing MHD and investigated its clinical utility in quantitatively analyzing left ventricular systolic function in patients with left ventricular hypertrophy secondary to MHD.[20] The findings demonstrated that GWE, GWW, GWI, and GCW exhibited significant area under the curve, sensitivity, and specificity in evaluating left ventricular function in patients undergoing MHD. This suggests that myocardial work parameters can quantitatively assess left ventricular myocardial function in this patient population.

However, myocardial work technology has several limitations. Notably, it substitutes brachial artery systolic pressure for left ventricular intracavitary pressure in the construction of the pressure-strain curve. In patients with elevated arterial pressure or brachial vascular disease, the use of a cuff to measure brachial systolic pressure may result in inaccurate readings. Furthermore, myocardial work relies on the integration of strain parameters derived from 2D-STE, which requires high-quality imaging. Additionally, there is currently no standardized reference value for myocardial work.

Microcirculatory Assessment and Stress Echocardiography

A frequently employed metric for evaluating microcirculatory impairment in CKD patients is coronary flow reserve (CFR). CFR denotes the capacity of coronary arteries to dilate in response to increased oxygen demand or the influence of neurohumoral factors and pharmacological agents, thereby facilitating an augmentation of coronary blood flow from a baseline to a hyperemic state.[54] CFR evaluated using pulsed Doppler echocardiography testing on the left anterior descending artery is the state-of-the-art method during vasodilatory stress echocardiography. This non-invasive test is characterized by high reproducibility, safety, and reliability, and it has been extensively adopted in clinical practice.[55,56]

An observational study encompassing 5966 patients with CKD and 1410 patients without CKD estimated the mean glomerular filtration rate (GFR) and mean CFR. The findings indicated a significant positive correlation between mean GFR and mean CFR, with CKD patients demonstrating markedly lower CFR compared to non-CKD patients.[57] This underscores the prevalent and progressive nature of coronary microvascular dysfunction (CMD) with worsening renal function. CFR, as a measure of microvascular integrity, directly reflects CMD, which is highly prevalent in CKD due to endothelial dysfunction, inflammation, and uremic toxins. Impaired CFR can exist even in the absence of significant epicardial coronary stenosis, contributing to symptoms like angina and adverse outcomes, and may explain negative stress tests in patients with typical symptoms.

While CFR primarily assesses microcirculatory function, Dobutamine Stress Echocardiography (DSE) is a well-established method for evaluating macrovascular coronary artery disease (CAD) by detecting regional myocardial wall motion abnormalities indicative of ischemia. Some scholars believe that stress echocardiography should be considered in all patients with CKD, including those with no obvious electrocardiogram abnormality.[10] DSE is an effective method for assessing the cardiovascular response to stress in subjects by examining myocardial viability and ischemia, providing valuable diagnostic and prognostic information for clinical purposes.[58]

DSE protocols typically involve a stepwise infusion of increasing doses of dobutamine (eg, 5–40 μg/kg/min) combined with continuous echocardiographic imaging to assess wall motion abnormalities at rest and during stress.[59] Atropine may be added if the target heart rate is not achieved with dobutamine alone. Patient selection for DSE in CKD often prioritizes individuals with intermediate pre-test probability of CAD, those with unexplained cardiac symptoms, or candidates for kidney transplantation, where comprehensive cardiovascular assessment is crucial.[59,60] The non-invasive nature and absence of nephrotoxic contrast agents make DSE particularly attractive in this patient population, especially when compared to contrast-enhanced modalities.

A meta-analysis that included 11 studies in 690 kidney transplant candidates on dialysis showed that dobutamine stress echocardiography had high sensitivity (80%) and specificity (89%) for the detection of coronary stenosis assessed using angiography; and importantly, it demonstrated advantages over myocardial perfusion scintigraphy which had a lower sensitivity (69%) and specificity (77%) in this specific high-risk cohort.[21] This comparative effectiveness highlights DSE's utility in CKD patients. A study involving 485 CKD patients (mean age 61 ± 14 years) demonstrated that the extent of ischemia detected through DSE is an independent predictor of overall mortality. Patients with extensive ischemia had lower one-year and three-year survival rates compared to those with milder ischemia or normal DSE results.[22]

However, the blunted chronotropic and inotropic response in advanced CKD patients, even with atropine administration, often makes it difficult to achieve the maximum predicted heart rate, which is essential for detecting inducible ischemia. This reduced ability to reach target heart rate significantly compromises the sensitivity of DSE in detecting myocardial ischemia in this population. This inherent physiological limitation, coupled with potential challenges in image quality due to comorbid conditions, hinders the clinical application and diagnostic yield of DSE in a substantial subset of these patients. In these cases, where DSE may be inconclusive, the independent assessment of CFR could provide additional critical information about the coronary circulation's functional capacity, especially if the blunted response is due to underlying microvascular impairment rather than macrovascular stenosis.

The co-existence of macrovascular CAD and microvascular dysfunction is common in CKD patients, making a single test insufficient for a complete assessment. A patient with impaired CFR but normal DSE might have isolated CMD, demanding different management strategies. Conversely, a positive DSE unequivocally points towards macrovascular CAD. Future research should focus on integrating multi-modality imaging approaches, combining macrovascular assessment (like DSE) with microvascular evaluation (like CFR), to provide a more comprehensive and prognostic risk stratification in CKD patients, ultimately guiding personalized management strategies.

Challenge and Outlook

Early monitoring of cardiac function in patients with CKD is essential for timely intervention, delaying the onset of cardiovascular complications, and reducing mortality rates. This is especially crucial in older adults, where age-related physiological changes can mask early symptoms of cardiovascular disease, leading to delayed diagnosis and intervention. However, age-related cardiac structural changes, including increased myocardial stiffness, concentric hypertrophy, and diastolic dysfunction, substantially impact echocardiographic parameters such as GLS and E/e' ratio. For instance, increased myocardial stiffness may elevate E/e' ratios, potentially leading to overestimation of left ventricular filling pressures if age-specific reference values are not considered. Similarly, GLS, which reflects myocardial deformation, may exhibit reduced values in the elderly even in the absence of pathological cardiomyopathy, necessitating age-adjusted interpretation thresholds to distinguish normal aging from disease processes. Furthermore, frailty and cognitive impairment may limit the patient's capacity to tolerate stress testing procedures, such as exercise or pharmacologic stress echocardiography. These conditions can also influence cooperation and image quality. In recognition of these challenges, clinicians should adopt age-specific normative data and carefully consider comorbidities when interpreting echocardiographic parameters in elderly CKD patients. Tailored assessment strategies, focusing on resting measurements and advanced imaging modalities, can improve diagnostic accuracy while minimizing patient burden.

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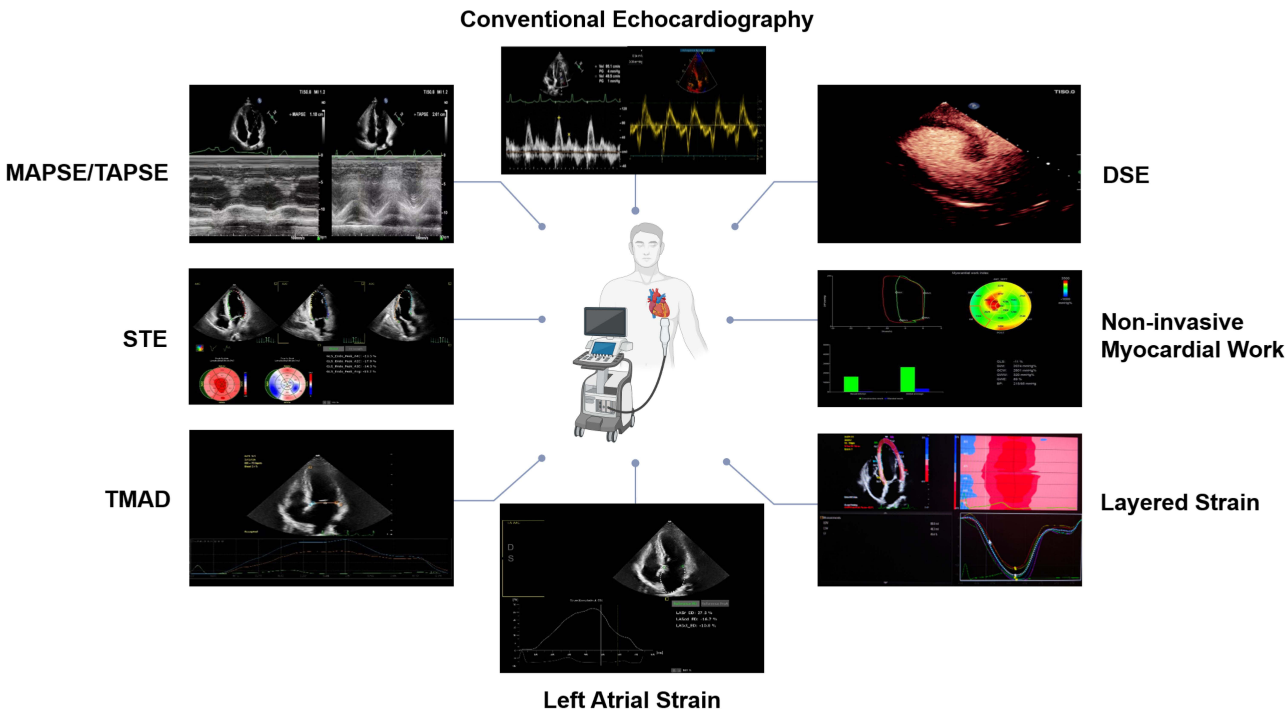

Figure 1 Various ultrasound techniques utilized for evaluating cardiac function in patients.

While advanced ultrasound techniques offer significant advantages in assessing cardiac function, it is imperative not to depend exclusively on ultrasound diagnostic results. A thorough evaluation should encompass additional imaging techniques, such as MRI, alongside clinical laboratory indicators, to furnish more dependable information for the early diagnosis of cardiovascular lesions. Looking ahead, future research should focus on establishing age-specific reference ranges for these advanced ultrasound parameters in CKD patients. Additionally, studies are needed to evaluate the impact of geriatric-specific interventions, such as exercise and nutritional support, on cardiac function as assessed by these advanced techniques. Furthermore, research exploring the cost-effectiveness of these advanced ultrasound modalities in the clinical management of elderly CKD patients would be highly valuable.

Conclusion

Echocardiography, which provides a thorough assessment of cardiac morphology and function, presents several advantages, including its non-invasive nature, cost-effectiveness, convenience, rapidity, and repeatability. This diagnostic tool has been extensively utilized in both scientific research and clinical practice. With the rapid advancement of ultrasound technology, novel ultrasound techniques are continuously being updated and refined. Emerging ultrasound modalities, such as STE and DSE, possess the capability to quantitatively assess subclinical dysfunction in patients with CKD at early stages of the disease (Figure 1). Additionally, these technologies facilitate real-time dynamic monitoring of cardiac function changes pre- and post-hemodialysis. In the context of geriatric care, these advanced techniques can be particularly beneficial for monitoring the impact of dialysis on frail patients with multiple comorbidities, allowing for more personalized treatment strategies. These techniques are instrumental in the early diagnosis, clinical intervention, and risk assessment of CKD-related cardiovascular disease, thereby offering expansive prospects for the evaluation of cardiac function.

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Disclosure

The authors have declared that no conflict of interest exists.

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