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LEFT ATRIAL MECHANICS ASSESSED BY SPECKLE-TRACKING ECHOCARDIOGRAPHY IN ADULT PATIENTS UNDERGOING HEMODIALYSIS: A SYSTEMATIC REVIEW

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ABSTRACT

Introduction: Cardiovascular disease remains the leading cause of morbidity and mortality in patients with end-stage renal disease undergoing maintenance hemodialysis. In this population, conventional echocardiographic parameters may not fully detect early atrial dysfunction or adequately reflect the complex hemodynamic effects of recurrent volume shifts. Speckle tracking echocardiography has emerged as a promising tool for the assessment of left atrial mechanics, including reservoir, conduit, and contractile function.
Methods: This systematic review was conducted in accordance with the PRISMA framework. A PubMed/MEDLINE search was performed using predefined terms related to left atrial strain, left atrial mechanics, speckle-tracking echocardiography, hemodialysis, and end-stage renal disease. Studies were eligible if they included adult patients undergoing maintenance hemodialysis and assessed left atrial deformation using speckle-tracking echocardiography. Seven studies met the inclusion criteria and were included in the qualitative synthesis.
Results: Across the included studies, left atrial strain was consistently impaired in adult hemodialysis patients and was associated with markers of diastolic dysfunction, elevated filling pressures, atrial remodeling, and dialysis-related loading changes. Left atrial reservoir strain emerged as the most clinically informative parameter and demonstrated independent prognostic value for major adverse cardiovascular events and mortality in prospective studies. In addition, impaired left atrial deformation and strain rate were associated with an increased risk of paroxysmal atrial fibrillation.
Conclusions: Left atrial mechanics assessed by speckle-tracking echocardiography appear to provide clinically relevant information in adult patients undergoing hemodialysis. Left atrial strain may serve as a sensitive imaging biomarker of subclinical cardiovascular dysfunction and may improve cardiovascular risk stratification in this population. However, further prospective multicenter studies are required to standardize methodology and confirm the role of left atrial strain in routine clinical practice.

KEYWORDS

Hemodialysis; End-Stage Renal Disease; Echocardiography; Speckle-Tracking; Left Atrium

CITATION

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Introduction

Chronic kidney disease (CKD) is strongly associated with a substantial increase in cardiovascular morbidity and mortality, and cardiovascular complications remain the leading cause of death across the spectrum of renal dysfunction. The cardiovascular burden of CKD is multifactorial and includes hypertension, vascular stiffness, endothelial dysfunction, inflammation, uremic toxicity, myocardial fibrosis, and chronic pressure and volume overload. As renal disease progresses, the interactionbetween renal and cardiovascular impairment becomes increasingly complex, particularly in patients with end-stage renal disease (ESRD), in whom cardiac structural and functional abnormalities are highly prevalent (Jankowski et al., 2021; Zoccali et al., 2023). In patients reaching ESRD, cardiovascular abnormalities are often already well established by the time renal replacement therapy is initiated. Classic echocardiographic studies demonstrated a high prevalence of left ventricular hypertrophy, chamber enlargement, and systolic or diastolic dysfunction in patients beginning ESRD therapy, highlighting the close relationship between renal failure and cardiac remodeling (Foley et al., 1995). In contemporary hemodialysis populations, the cardiovascular phenotype remains shaped not only by long-term uremic cardiomyopathy but also by repeated intradialytic and interdialytic fluctuations in preload, afterload, blood pressure, and electrolyte balance. These factors create a particularly challenging setting for cardiac assessment, as static measures of chamber size do not always capture dynamic myocardial dysfunction. Echocardiography is central to cardiovascular evaluation in CKD and ESRD because it is noninvasive, widely available, repeatable, and able to characterize both cardiac structure and function. Conventional echocardiographic measures such as left ventricular ejection fraction, wall thickness, transmitral flow indices, tissue Doppler velocities, and left atrial volume continue to play an important role in routine clinical practice. However, in patients with CKD and especially in those undergoing hemodialysis, these measures may be limited by loading dependence and may fail to detect early myocardial dysfunction before overt structural abnormalities appear (Sulemane et al., 2017). Standard chamber quantification remains essential and should be interpreted according to established recommendations for adult echocardiography (Lang et al., 2015), yet there is increasing interest in parameters that may provide a more sensitive functional assessment. Among advanced echocardiographic techniques, speckle-tracking echocardiography (STE) has gained considerable attention as a method for the quantitative analysis of myocardial deformation. STE permits angle-independent assessment of myocardial mechanics and can be applied not only to the left ventricle but also to the left atrium. Because the left atrium acts as a reservoir during ventricular systole, a conduit during early diastole, and a contractile booster pump during late diastole, deformation imaging provides a physiologically meaningful way to quantify each phase of atrial function. Importantly, consensus efforts have emphasized the need for standardization in atrial deformation imaging, particularly in relation to acquisition, analysis, timing conventions, and reporting of strain parameters (Badano et al., 2018). The left atrium is especially relevant in ESRD and maintenance hemodialysis because it reflects the cumulative effects of left ventricular filling pressure, diastolic dysfunction, chamber stiffness, and volume overload. Left atrial enlargement has long been recognized as a marker of chronic diastolic burden, yet left atrial strain may offer earlier and more nuanced information than volume-based indices alone. This is clinically important in hemodialysis patients, in whom atrial size may vary with volume status and in whom subclinical dysfunction may precede overt enlargement. Accordingly, left atrial mechanics assessed by STE may represent a more sensitive marker of cardiovascular involvement in this population.

The emerging body of literature supports this possibility. In adults undergoing chronic hemodialysis, left atrial strain has been linked to conventional indices of diastolic dysfunction, left atrial volume, and biomarkers such as brain natriuretic peptide. In one early study of ESRD patients with preserved left ventricular ejection fraction receiving chronic hemodialysis, left atrial global peak systolic strain decreased in parallel with worsening systolic and diastolic function and showed significant associations with BNP and echocardiographic indices of filling pressure, suggesting that atrial deformation may complement standard diastolic assessment. Another study demonstrated that left atrial myocardial deformation in hemodialysis

patients with preserved systolic function wasindependently associated with echocardiographically estimated pulmonary capillary wedge pressure, reinforcing the potential of LA mechanics as a marker of left ventricular dysfunction. Subsequent studies expanded the clinical scope of left atrial strain in hemodialysis. In a cross-sectional comparison of renal transplant recipients and matched maintenance hemodialysis patients, all main left atrial strain phases were more favorable in the transplant group, implying that chronic hemodialysis is associated with more impaired atrial mechanics. Other investigations focused on the acute effects of dialysis itself and showed that left atrial reservoir and conduit strain may decline after a hemodialysis session, indicating sensitivity to short-term loading changes and highlighting the importance of timing echocardiographic acquisition relative to dialysis. Most importantly, several studies suggest that left atrial strain is not merely a descriptive echocardiographic measurement but may carry prognostic relevance. Reduced left atrial reservoir strain assessed by three-dimensional STE was identified as an independent predictor of major adverse cardiovascular events and cardiac death in maintenance hemodialysis patients, with performance superior to some traditional left atrial and left ventricular indices. In another prospective study, impaired left atrial deformation indices were associated with the occurrence of paroxysmal atrial fibrillation in ESRD patients, underscoring the arrhythmic implications of atrial dysfunction. More recently, four-dimensional STE data from stable dialysis patients with preserved ejection fraction also suggested that impaired left atrial reservoir mechanics were independently associated with all-cause mortality or major adverse cardiovascular events. Despite these promising findings, the literature remains relatively limited and heterogeneous. Existing studies differ in population characteristics, dialysis timing, echocardiographic protocols, STE dimensionality, reported strain parameters, and clinical endpoints. Some focus on pathophysiologic correlations, while others evaluate prognostic performance or acute changes induced by dialysis. This heterogeneity makes it difficult to determine the overall clinical utility of left atrial strain in adult hemodialysis patients and limits straightforward translation into routine clinical practice. Therefore, the aim of this systematic review was to synthesize the available evidence regarding left atrial mechanics assessed by speckle-tracking echocardiography in adults undergoing hemodialysis. Particular attention was paid to the clinical usefulness of left atrial strain parameters in relation to cardiac structure and function, dialysis-related loading conditions, and adverse cardiovascular outcomes.

Material and Methods

This systematic review was conducted to evaluate the clinical utility of left atrial mechanicsassessed by speckle-tracking echocardiography in adult patients undergoing hemodialysis. The review was designed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, and the study selection process was structured according to the PRISMA flow approach.

Search strategy

A systematic literature search was performed in **PubMed/MEDLINE** to identify studies investigating left atrial strain or left atrial mechanics in adult patients undergoing hemodialysis. Thesearch strategy combined terms related to left atrial deformation, speckle-tracking echocardiography, and hemodialysis/end-stage renal disease. Filters for **Humans** and **English language** were applied manually in the PubMed interface during screening. The search was designed to maximize retrieval of studies specifically assessing left atrial mechanics in adult hemodialysis populations while minimizing inclusion of studies focused exclusively on chronic kidney disease without dialysis, pediatric cohorts, or studies centered on ventricular strain without relevant left atrial data.

Eligibility criteria

Studies were considered eligible for inclusion if they met all of the following criteria:

1. included adults aged 18 years or older;
2. enrolled patients undergoing maintenance hemodialysis or reported a clearly identifiable adult hemodialysis subgroup;
3. assessed left atrial mechanics, left atrial strain, or left atrial deformation using speckle-tracking echocardiography;
4. reported original clinical data;
5. were available as full-text articles in English.

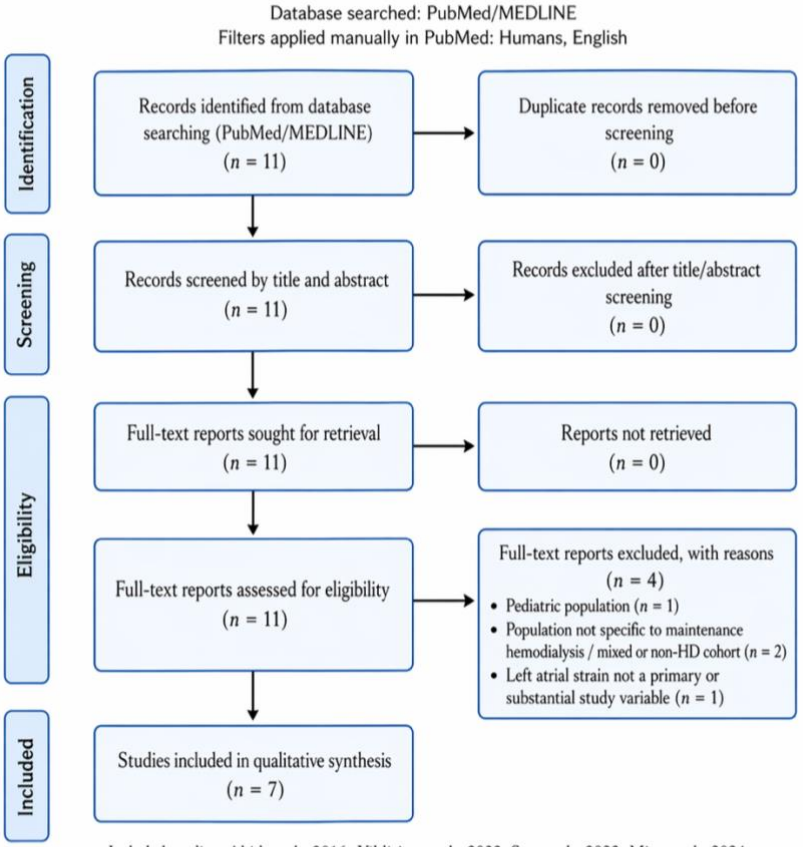
Studies were excluded if they:

1. included pediatric populations only;
2. focused on chronic kidney disease or end-stage renal disease without a clearly defined maintenance hemodialysis population;
3. evaluated ventricular strain only, without meaningful left atrial deformation data;
4. were reviews, editorials, letters, conference abstracts, or case reports;
5. did not provide sufficient methodological or outcome data for qualitative synthesis.

Study selection

The search yielded 11 records from PubMed/MEDLINE. No duplicate records were identified. Therefore, 11 records were screened on the basis of title and abstract. At this stage, no studies were excluded because all retrieved records were considered potentially relevant to the review question and underwent full-text assessment. As a result, 11 full-text articles were sought and successfully retrieved, and all 11 reports were assessed for eligibility. After detailed full-text review, 4 studies were excluded. The reasons for exclusion were as follows: pediatric population(n = 1), population not specific to maintenance hemodialysis or mixed/non-hemodialysis cohort (n = 2), and left atrial strain not being a primary or substantial study variable (n = 1). Finally, 7 studies were included in the qualitative synthesis. Figure 1. PRISMA flow diagram of study selection. The final review corpus consisted of the following studies: Abid et al. (2016), Yildirim et al. (2022), Sun et al. (2022), Miao et al. (2024), Altekin et al. (2013), Papadopoulos et al. (2018), and Li et al. (2024).

Figure 1. PRISMA flow diagram of study selection



Included studies: Abid et al., 2016; Yildirim et al., 2022; Sun et al., 2022; Miao et al., 2024; Altekin et al., 2013; Papadopoulos et al., 2018; Li L et al., 2024.

PubMed search strategy

(("left atrial strain" OR "left atrial reservoir strain" OR "left atrial conduit strain" OR "left atrial contractile strain" OR "left atrial mechanics" OR "atrial strain" OR "LA strain") AND ("speckle tracking echocardiography" OR "speckle-tracking echocardiography" OR "speckle tracking" OR "two-dimensional speckle tracking echocardiography" OR "2D speckle tracking echocardiography" OR "echocardiography, speckle tracking"[Mesh]) AND ("hemodialysis" OR "haemodialysis" OR "maintenance hemodialysis" OR "Hemodialysis"[Mesh] OR "Renal Dialysis"[Mesh] OR "end-stage renal disease" OR "end stage renal disease" OR ESRD))

Data extraction

For each included study, the following information was extracted: first author and year of publication, study design, sample size, patient characteristics, dialysis-related characteristics, echocardiographic methodology, dimensionality of speckle-tracking analysis, left atrial strain parameters, comparator groups if applicable, and the principal echocardiographic and clinical findings. Particular attention was given to whether left atrial strain parameters provided clinically relevant information regarding: left ventricular diastolic dysfunction, filling pressures, left atrial remodeling, intradialytic or interdialytic volume-related changes, arrhythmic risk, major adverse cardiovascular outcomes.

Data synthesis

Because the included studies differed substantially in study design, population characteristics, timing of echocardiography in relation to dialysis, strain methodology, and reported outcomes, a quantitative meta-analysis was not considered appropriate. Therefore, the findings were synthesized narratively. The qualitative synthesis focused on the following domains:

1. impairment of left atrial strain in adult hemodialysis patients;
2. association between left atrial strain and conventional echocardiographic parameters;
3. association between left atrial strain and diastolic dysfunction;
4. influence of hemodialysis-related loading conditions on left atrial mechanics;
5. prognostic value of left atrial strain for cardiovascular events and arrhythmias.

Methodological considerations

Several limitations of the available evidence were taken into account during interpretation. Most included studies were single-center investigations with relatively small sample sizes. In addition, the timing of echocardiographic assessment varied considerably across studies, with some performing measurements before dialysis, others after dialysis, and others during stable follow-up. This is particularly relevant because left atrial mechanics are sensitive to loading conditions and volume shifts, which are intrinsic to the hemodialysis setting. Another important source of heterogeneity was the echocardiographic methodology itself. The included studies used two-dimensional, three-dimensional, or four-dimensional speckle-tracking echocardiography, and reported different combinations of reservoir, conduit, and contractile strain parameters. These methodological differences were considered when comparing results across studies and when interpreting the overall clinical utility of left atrial strain in this population.

Results

Seven studies met the inclusion criteria and were included in the qualitative synthesis. The evidence base comprised predominantly single-center observational studies and covered several distinct clinical contexts: cross-sectional assessment of left atrial mechanics in chronic hemodialysis, comparison between hemodialysis and renal transplantation, evaluation of intradialytic changes, and prospective analyses of arrhythmic or cardiovascular outcomes. Most studies used two-dimensional speckle-tracking echocardiography, whereas Sun et al. (2022) applied three-dimensional speckle-tracking echocardiography and Li et al. (2024) used dedicated four-dimensional speckle-tracking analysis. Across the included studies, left atrial mechanics were most commonly described through reservoir, conduit, and contractile phases, although Abid et al. (2016) reported left atrial global peak systolic strain (LAGS) as a summary marker of atrial deformation.

Left atrial strain is consistently impaired in adult hemodialysis populations

A recurring finding across the included studies was that left atrial strain was reduced in patients with ESRD undergoing hemodialysis, even in cohorts with preserved left ventricular ejection fraction. Altekin et al. (2013) showed markedly lower left atrial systolic, early diastolic, and late diastolic strain in ESRD patients than in healthy controls: LAS-S 32.22 ±7.64% versus 57.93 ±8.71%, LAS-E −15.86 ±5.70% versus −33.37 ±7.71%, and LAS-A −15.41 ±4.16% versus −24.57 ± 4.68%, all with p <.001. In the same study, left atrial stiffness was substantially higher in ESRD patients than in controls (0.40 ±0.19 vs. 0.17 ±0.05, p <.001), suggesting a mechanically less compliant atrium in the dialysis population. Clinically, these findings support the concept that LA deformation imaging detects functional abnormalities beyond conventional volumetric assessment alone (Altekin et al., 2013). Similarly, Miao et al. (2024) demonstrated that before hemodialysis, ESRD patients already had significantly lower atrial strain than healthy controls. Pre-dialysis median LASr

was 28.0 (23.0, 34.5) compared with 43.0 (36.0, 48.0) in controls, LAScd was −15.5 (−10.0, −21.5) versus −24.0 (−18.0, −32.0), and LASct was −12.0 (−9.0, −16.0) versus −17.0 (−15.0, −22.0), with statistically significant differences for all three phases. The authors interpreted these findings as evidence that atrial dysfunction may already be detectable when more conventional functional indices are less informative, reinforcing the role of LA strain as a sensitive marker of subclinical cardiac involvement in ESRD (Miao et al., 2024). Additional support comes from Yildirim et al. (2022), who compared renal transplant recipients with age- and sex-matched patients on maintenance hemodialysis. LA mechanics were consistently worse in the hemodialysis group: LASr 26.11 ±5.74% versus 29.88 ±5.76% in transplant recipients (P <.001), LAScd −12.92 ±4.38% versus −15.28 ±5.00% (P =.003), and LASct −13.19 ±3.95% versus −14.60 ±3.32% (P =.020). Strain-rate indices showed the same pattern, with all phasic SR parameters significantly less favorable in the hemodialysis cohort. Although the study was comparative rather than prognostic, the results suggest that chronic dialysis exposure is associated with more impaired atrial mechanics and that LA deformation may reflect the cumulative cardiovascular burden of ESRD more sensitively than standard structural indices alone (Yildirim et al., 2022).

Association with diastolic dysfunction, filling pressures, and atrial remodeling

Several included studies indicate that LA strain parameters are closely linked to left ventricular diastolic dysfunction and left-sided filling pressure. In Abid et al. (2016), 30 chronic hemodialysis patients with preserved LVEF underwent echocardiography immediately before and after dialysis.Before hemodialysis, LAGS showed significant inverse correlations with BNP (r = −0.482, p =.007), E/E′ (r = −0.33, p =.049), LAVmax (r = −0.366, p =.047), and LAVmin (r= −0.579, p =.001), while correlating positively with E′ velocity (r = 0.557, p =.001) and LA ejection fraction (r= 0.58, p =.001). BNP values were significantly higher before dialysis and decreased after hemodialysis, whereas LAEF and LAGS increased after the session. Taken together, these findings suggest that impaired atrial deformation mirrors higher filling pressures, worse diastolic function, and less favorable atrial hemodynamics. In clinical terms, LAGS appeared to behave as a complementary functional marker of diastolic burden rather than simply an anatomical descriptor of chamber size (Abid et al., 2016). Altekin et al. (2013) further strengthened this interpretation by directly relating atrial deformation to estimated pulmonary capillary wedge pressure. In that study, associations were found between ePCWP and LAS-S (p <.001), LAS-E (p =.01), LAS-A (p <.001), and LA stiffness (p <.001). Moreover, among ESRD patients stratified by left atrial volume index, those with LAVI >31.34 mL/m² had lower LAS-S (30.36 ±8.32% vs. 34.11 ±6.43%, p =.023) and LAS-E (−14.97 ±5.88% vs.−16.76 ±5.42%, p =.039), while LAS-A and LA stiffness were higher. This pattern suggests that LA deformation not only reflects current filling pressure but also tracks structural remodeling. The clinical implication is important: LA strain may identify functional deterioration before volumetric enlargement alone fully captures the severity of atrial involvement (Altekin et al., 2013).

Sensitivity of left atrial mechanics to acute hemodialysis-related loading changes

One of the most clinically relevant findings in the review is the apparent load sensitivity of LA strain in the hemodialysis setting. Miao et al. (2024) specifically assessed atrial strain before and after a single hemodialysis session in 76 ESRD patients. Post-dialysis LASr fell from a median of 28.0 to 26.0 (p =.003), and LAScd from −15.5 to −12.0 (p =.006), whereas LASct remained essentially unchanged (−12.0 vs. −12.5, p =.965). The authors concluded that passive atrial functions—reservoir and conduit components—were strongly influenced by acute preload reduction, while contractile deformation was relatively preserved. This distinction is clinically meaningful because it suggests that not all atrial strain phases should be interpreted equally in dialysis patients, particularly when image acquisition timing relative to dialysis is not standardized (Miao et al., 2024). Abid et al. (2016) reported a similar directional observation using LAGS rather than phased strain parameters. In their cohort, BNP values, LA dimensions, and LA volumes decreased after hemodialysis, while LAEF and LAGS increased. Although the parameterization differs from that used by later studies, both reports indicate that LA mechanics are dynamically altered by fluid removal and therefore highly sensitive to acute hemodynamic state. From a practical standpoint, this means that the clinical interpretation of LA strain in hemodialysis patients must take into account the exact timing of the echocardiographic examination, as the same patient may show different deformation characteristics before versus after dialysis (Abid et al., 2016; Miao et al., 2024).

Prognostic significance for cardiovascular events

Among the included studies, the strongest evidence for prognostic utility came from Sun et al. (2022) and Li et al. (2024). In the prospective 3DSTE study by Sun et al. (2022), 130 maintenance hemodialysis patients were followed for a median of 40.5 months, and 43 reached the composite endpoint of major adverse cardiovascular events. Patients with events had larger indexed LA maximal volume (45.1 ±11.9 vs. 33.8 ± 6.9 mL/m²) and significantly lower LA strain values: LASr 20.2 ±3.5% versus 27.2 ±3.3%, LAScd −12.3 ± 5.2% versus −14.5 ±4.0%, and LASct −8.0 ±4.2% versus −13.2 ±3.7%, all p <.05. In multivariable Cox analysis, LASr emerged as the strongest predictor of MACEs, with a hazard ratio of 0.69 (95% CI [0.54, 0.89], p =.004), and Kaplan–Meier analysis showed significantly higher event incidence in patients with impaired LASr below 24.2%. Importantly, the authors concluded that LASr was superior to LV parameters and LA volume indices for risk prediction. This strongly supports the idea that LA reservoir strain is not merely a descriptive marker of atrial function but a clinically relevant prognostic biomarker in maintenance hemodialysis (Sun et al., 2022). Li et al. (2024) extended the prognostic evidence by applying dedicated 4DSTE in 80 stable dialysis patients with preserved LVEF. Over a median follow-up of 19 months, the event group had lower longitudinal LASr (16.4% vs. 21.2%, P =.0003), lower LASct (8.2% vs. 11.2%, P =.01), lower circumferential LASr_c (25.2% vs. 35.0%, P =.0004), and lower LASct_c (14.9% vs. 20.9%, P =.001). In contrast, conduit-phase parameters were less discriminative. Multivariable Cox regression identified LASr (HR = 0.81, P =.0005 per 1% increase) and LASr_c (HR = 0.93, P =.01 per 1% increase) as independent predictors of all-cause mortality or MACEs. The study also proposed clinically useful thresholds, with LASr <18.5% and LASr_c <28.5% associated with a higher risk of adverse outcomes. These findings suggest that reservoir-phase impairment remains the most prognostically informative component even when more advanced multidimensional atrial analysis is used, and they additionally raise the possibility that circumferential deformation may offer incremental prognostic value in selected dialysis populations (Li et al., 2024).

Association with arrhythmic risk

Papadopoulos et al. (2018) provided specific insight into the arrhythmic relevance of atrial deformation. In a cohort of 79 ESRD patients with preserved LV systolic function, followed for a mean of 16 ±5 months, 15 of the 70 survivors experienced one or more episodes of paroxysmal atrial fibrillation. Compared with patients without PAF, those with PAF had larger indexed LA volumes (32 ±26 vs. 21.5 ±9 mL/m², p =.002), lower mean LA strain (17 ±7 vs. 27 ±9%, p <.001), and lower mean LA strain rate (−1.19 ±0.5 vs. −1.95 ± 0.5 s^{-1}, p <.001). In multivariable analysis, LA strain rate adjusted for age and previous PAF history remained the single most significant echocardiographic predictor of PAF. This indicates that atrial deformation indices may identify a subgroup of ESRD patients at particularly high arrhythmic risk, potentially before overt clinical AF becomes evident. In practical terms, LA strain rate may have value for early rhythm-risk phenotyping and closer surveillance in hemodialysis populations (Papadopoulos et al., 2018).

Overall pattern across included studies

Taken together, the included studies show a consistent pattern: left atrial deformation is impaired in adult hemodialysis patients, relates closely to diastolic dysfunction and atrial remodeling, changes acutely with dialysis-related loading shifts, and carries clinically meaningful prognostic information. Across different imaging approaches—2D, 3D, and 4D STE—the most consistently informative parameter was reservoir-phase strain, although contractile-phase impairment also appeared relevant in more advanced prognostic analyses and strain-rate parameters were particularly important for arrhythmic prediction. Overall, the body of evidence suggests that LA strain provides information that is functionally richer than left atrial volume alone and may improve cardiovascular phenotyping and risk stratification in the hemodialysis setting (Abid et al., 2016; Altekin et al., 2013; Papadopoulos et al., 2018; Sun et al., 2022; Li et al., 2024).

Discussion

The present systematic review indicates that left atrial mechanics assessed by speckle-tracking echocardiography provide clinically meaningful information in adult patients undergoing hemodialysis. Across the seven included studies, left atrial strain was consistently impaired, associated with conventional markers of adverse cardiac structure and function, sensitive to acute loading changes induced by dialysis, and in several cohorts demonstrated prognostic relevance for arrhythmias, major adverse cardiovascular events, and mortality. Taken together, these findings support the view that left atrial strain is not merely an additional echocardiographic parameter, but a potentially valuable imaging biomarker of cardiovascular vulnerability in the hemodialysis population. A central observation emerging from this review is that LA strain appears to identify atrial dysfunction even in patients with preserved left ventricular ejection fraction. This is clinically important because conventional echocardiographic assessment in dialysis patients may underestimate early dysfunction when based primarily on chamber size, ejection fraction, or Doppler-derived indices alone. In the included studies, impaired atrial deformation was repeatedly observed despite preserved LVEF, indicating that left atrial mechanics may capture an earlier and more subtle stage of cardiovascular involvement. In practical terms, this suggests that LA strain could help detect subclinical cardiac dysfunction before overt structural remodeling or advanced symptomatic heart disease becomes fully apparent. Such a role is particularly relevant in hemodialysis patients, in whom cardiovascular disease often evolves silently but has major prognostic consequences (Abid et al., 2016; Altekin et al., 2013; Papadopoulos et al., 2018; Li et al., 2024). Another major theme concerns the close relationship between left atrial strain and diastolic burden. Several included studies showed that reduced LA deformation tracked with higher filling pressures, worse diastolic indices, larger atrial volumes, and less favorable atrial functional performance. This is physiologically plausible because the left atrium is continuously exposed to the consequences of chronically elevated left ventricular filling pressure, myocardial stiffness, and impaired relaxation. Unlike static measurements of atrial size, deformation imaging reflects the phasic mechanical behavior of the atrial wall and may therefore provide a more direct functional representation of diastolic stress. The correlations reported by Abid et al. (2016) between LAGS and BNP, E/E′, and LA volumes, together with the associations between strain and estimated pulmonary capillary wedge pressure reported by Altekin et al. (2013), strongly support the notion that LA strain behaves as a functional marker of diastolic dysfunction rather than simply a structural marker of chamber enlargement. This may be one of the most clinically useful features of LA strain in hemodialysis patients. In everyday echocardiographic practice, assessment of diastolic dysfunction in ESRD is often challenging because conventional parameters are influenced by preload variation, arterial stiffness, and coexisting ventricular remodeling. Atrial deformation analysis may help refine this evaluation by integrating the cumulative mechanical consequences of chronic pressure and volume burden. From a clinical standpoint, this means that LA strain could complement rather than replace standard echocardiographic parameters, offering an additional layer of risk-oriented interpretation, especially in patients whose conventional findings are borderline or difficult to classify. The sensitivity of left atrial strain to acute dialysis-related loading changes represents both an opportunity and a limitation. Miao et al. (2024) showed that reservoir and conduit strain declined after hemodialysis, while Abid et al. (2016) also documented significant post-dialysis changes in atrial function and chamber dimensions. These results indicate that LA mechanics are highlydynamic in response to fluid removal and altered preload. On one hand, this may be advantageous: in a population characterized by marked volume fluctuation, LA strain may offer a physiologically responsive marker of loading state and functional adaptation. On the other hand, the same property complicates interpretation and comparability across studies. If strain values change substantially depending on whether echocardiography is performed before dialysis, after dialysis, or on a non-dialysis day, then timing becomes a crucial methodological variable. This is likely one reason why direct comparison of reported strain values across the literature remains difficult. Accordingly, any future clinical implementation of LA strain in maintenance hemodialysis should be accompanied by clear standardization of acquisition timing relative to the dialysis session. A particularly important result of this review is the emerging prognostic value of left atrial strain. Among the included studies, Sun et al. (2022) and Li et al. (2024) provided the strongest evidence that impaired reservoir-phase strain is associated with adverse cardiovascular outcomes and mortality. In both studies, reduced LASr independently predicted future events, and in the study by Sun et al. (2022), LASr outperformed traditional LA volume indices and selected LV parameters. These findings are clinically significant because they suggest that LA strain may carry information that is not fully captured by conventional echocardiographic markers. If confirmed in larger prospective studies, this would place atrial deformation in a more prominent role within cardiovascular risk stratification in hemodialysis patients. Rather than serving only as a descriptive marker of atrial mechanics, LASr may

function as an integrative signal of atrial compliance, ventricular interaction, diastolic burden, and cumulative cardiovascular stress. The prognostic implications of atrial deformation extend beyond heart failure physiology and into rhythm risk. Papadopoulos et al. (2018) showed that reduced LA strain and particularly reduced LA strain rate were strongly associated with paroxysmal atrial fibrillation in ESRD patients, with LA strain rate remaining the strongest echocardiographic predictor in multivariable analysis. This is clinically relevant because atrial fibrillation in the hemodialysis population is associated with substantial therapeutic complexity, including difficult anticoagulation decisions, elevated stroke risk, and frequent coexistence of structural heart disease. A marker capable of identifying a subgroup prone to AF before clinically evident sustained arrhythmia develops would have genuine clinical value. In this context, LA deformation may help characterize an arrhythmogenic substrate linked to atrial remodeling, pressure burden, and fibrosis, all of which are common in ESRD. An additional strength of the reviewed literature is that different study designs converged on a similar conclusion. Cross-sectional studies showed impaired atrial mechanics compared with controls or transplant recipients. Dialysis session studies showed that atrial deformation responds to acute hemodynamic shifts. Prospective studies linked impaired strain to MACEs, mortality, and arrhythmias. This convergence increases confidence that the observed abnormalities are not incidental technical findings but reflect clinically meaningful pathophysiology. Even so, the evidence base remains relatively small, and the apparent consistency of direction should not be mistaken for methodological uniformity. Several limitations of the current evidence should therefore be acknowledged. First, most included studies were single-center investigations with modest sample sizes. This increases the possibility of selection bias and limits generalizability. Second, the populations were not fully homogeneous. Some studies included only patients with preserved LVEF, whereas others enrolled broader dialysis populations. Third, the imaging methodology varied substantially, including 2D, 3D, and 4D speckle-tracking echocardiography, along with different strain conventions and phase definitions. Fourth, the timing of echocardiographic acquisition relative to dialysis was inconsistent, which is especially important given the marked load sensitivity of LA mechanics. Finally, the number of studies with hard clinical endpoints remains limited, and although the available results are promising, they are not yet sufficient to establish definitive cutoffs or universal prognostic algorithms. These limitations have direct implications for practice. At present, LA strain should probably be viewed as an advanced complementary parameter rather than a routine standalone decision-making tool in all hemodialysis patients. Its main current value lies in enhanced cardiovascular phenotyping: identifying subclinical atrial dysfunction, strengthening interpretation of diastolic burden, and potentially refining risk assessment in selected patients. The evidence reviewed here suggests that reservoir-phase strain is the most consistently informative measure, while conduit and contractile components may provide additional nuance depending on the clinical context. Strain rate may be particularly useful when arrhythmic risk is of concern. However, before routine implementation can be recommended, the field needs greater standardization in acquisition and reporting, better vendor harmonization, and prospective multicenter studies evaluating incremental value over established echocardiographic and clinical risk markers.

From a broader perspective, the results of this review support the concept that left atrial mechanics occupy a meaningful place at the intersection of hemodynamics, myocardial remodeling, and clinical prognosis in ESRD. The left atrium is not merely a passive chamber enlarged by chronic pressure exposure; rather, its deformation profile appears to summarize several dimensions of cardiovascular stress that are especially relevant in patients exposed to repeated dialysis-related fluid shifts. Because of this integrative character, LA strain may prove particularly attractive in a disease setting where conventional single-parameter assessment often fails to reflect the full complexity of cardiovascular risk.

In summary, the currently available evidence suggests that left atrial strain assessed by speckle-tracking echocardiography has genuine clinical promise in adults undergoing hemodialysis. It appears useful for detecting early atrial dysfunction, complements the assessment of diastolic abnormalities, reflects acute volume-related changes, and may help predict adverse cardiovascular and arrhythmic outcomes. At the same time, the evidence remains insufficiently standardized for immediate universal adoption. Future studies should focus on larger prospective cohorts, uniform timing of echocardiographic acquisition, standardized deformation methodology, and direct comparison of LA strain with established clinical and echocardiographic risk markers. Only then will it be possible to determine whether LA strain should move from being an advanced research parameter to becoming a routine component of cardiovascular assessment in the hemodialysis population.

Conclusions

Left atrial mechanics assessed by speckle-tracking echocardiography appear to provide clinically relevant information in adult patients undergoing hemodialysis. Across the studies included in this review, left atrial strain was consistently impaired and was associated with markers of diastolic dysfunction, elevated filling pressures, atrial remodeling, and dialysis-related loading changes. In addition, reduced left atrial deformation—particularly reservoir-phase strain—showed prognostic value for major adverse cardiovascular events, mortality, and paroxysmal atrial fibrillation. These findings suggest that left atrial strain may serve as a sensitive imaging biomarker of subclinical cardiovascular dysfunction in the hemodialysis population, offering information beyond conventional echocardiographic parameters such as chamber volume or left ventricular ejection fraction. Its potential clinical utility appears to be greatest in three areas: early detection of atrial dysfunction, refinement of cardiovascular risk stratification, and improved interpretation of cardiac function in the setting of fluctuating volume status. However, the currently available evidence remains limited by small sample sizes, predominantly single-center study designs, heterogeneity in imaging methodology, and inconsistent timing of echocardiographic assessment in relation to dialysis sessions. Therefore, although the results are promising, left atrial strain cannot yet be considered a fully standardized routine tool in the cardiovascular evaluation of hemodialysis patients. Further prospective multicenter studies are needed to confirm its incremental clinical value, establish standardized acquisition and reporting protocols, and determine how best to integrate left atrial strain into routine echocardiographic assessment and long-term risk prediction in adult patients undergoing maintenance hemodialysis.

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