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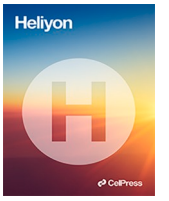

Review article

Application of left atrial strain derived from cardiac magnetic resonance feature tracking to predict cardiovascular disease: A comprehensive review

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A B S T R A C T

The structural and functional changes of the left atrium (LA)are important for maintaining the filling of the left ventricle (LV), whether the hemodynamics is stable or not, and are valuable for evaluating LV diastolic dysfunction and grading the severity. Studies over the past decade have shown that LA structural alterations are linked to several cardiovascular disorders, and LA enlargement has been identified as a strong predictor of several cardiovascular diseases. However, LA structural or volumetric abnormalities are commonly seen in the advanced stages of disease and do not adequately represent functional changes throughout the cardiac cycle. In recent years, LA strain obtained using cardiac magnetic resonance feature tracking (CMR-FT)technology has been shown to provide early monitoring of LA tension damage while also comprehensively reflecting LA functional changes in three phases, providing deeper insights into cardiovascular disease risk, prognosis of cardiovascular disease, and evaluation of therapeutic efficacy. When compared to the ultrasound speckle tracking approach, the CMR-FT technique provides improved spatial resolution, repeatability, and reproducibility. We report a comprehensive review of the most recent studies on CMR-LA strain in the past five years, including normal reference values, early detection of disease, incremental diagnosis, improvement of risk stratification, assessment of the value of atrial-ventricular hemodynamics and coupled injury, major adverse cardiovascular events and prognostic value, as well as future research perspectives and current limitations, aiming at providing an objective reference for the further exploration of the value of the application of CMR-LA strain in various cardiac disorders.

1. Introduction

The left atrium (LA)is important for maintaining left ventricle (LV)perfusion and hemodynamic stability, and its dysfunction and structural remodeling can be used as a sensitive marker to respond to LV diastolic dysfunction and severity grading. LA function can be divided into three consecutive temporal phases based on hemodynamic characteristics as follows: the reservoir phase (collect blood from the pulmonary veins collects during LV systole and isovolumic diastole to maintain left ventricular filling); conduit phase (in early diastole when the mitral valve is open, the atrium serves as a conduit through which the blood is passively pumped to the ventricle); and booster phase (at the end of diastole the atrium actively contracts and pumps the remaining blood into the LV) [1].CMR-derived LA strain and strain rate can quantitatively assess atrial function in three phases. Because of the peculiar orientation of the fibers and thinness of the atrial wall, only longitudinal strain of the atria is usually measured [1]. The parameters mainly include reservoir strain (LA εs), peak positive strain rate (SRs), conduit strain (LA εe), peak early negative strain rate (SRe), booster strain (LA εa), and peak late negative strain rate (SRa).

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The speckle tracking technique of ultrasound to obtain LA strain has been applied to the assessment of the function of each temporal phase in the cardiac cycle, which can reflect the early LA function impairment due to cardiovascular diseases and is of great clinical significance for the prognostic assessment and risk stratification of the disease [2,3]. However, it is susceptible to the influence of acoustic window, requires high image quality and acquisition frame rate, and is not very reproducible, which limits its wide application in clinical practice, whereas CMR-FT-derived LA strain has higher spatial resolution, higher tracking quality, and good reproducibility, which is more conducive to the promotion of clinical application [4].

Recently, several studies [5–8] demonstrated that assessing atrial function using CMR-FT can reveal early LA functional impairment in patients with cardiovascular disease and provide incremental diagnostic value, thereby offering deeper insights into disease risk stratification, assessment of the value of atrial-ventricular hemodynamics and coupled injury, major adverse cardiovascular events (MACE) occurrence, and prognosis prediction.

We aimed to review the research on CMR-FT-derived LA strain and evaluate the importance of its clinical application in the last 5 years.

2. CMR-FT-derived LA strain measurement and normal reference values

LA strain and strain rate parameters are usually obtained after plotting the LA inner and outer membrane contours on standard cine CMR images of two- and four-chamber views, which requires long image post-processing time and limits its clinical application to some extent. Leng et al. [9] reported the feasibility of fast LA long-axis strains (LA-las), which do not need to be fully depicted on LA contours although can be obtained by automatically tracking three reference points (the left atrioventricular junction and a user-defined point at the mid-posterior LA wall) (see Fig. 1). They showed excellent feasibility and effectiveness compared with standard CMR-FT, with a 55% reduction in evaluation time.

Some scholars [6,10–14] assessed LA strain in healthy volunteers (see Table 1). These results show the variability and lack of standardized LA strain parameter values between Medis and CVI42 post-processing software, which limits the widespread use of atrial strain analysis. We also attempted to measure LA strain and strain rate in the same healthy volunteers using both types of post-processing software (see Fig. 2a and b). Notably, Pathan et al. [15] compared the differences in atrial strain measurements between TTE and CMR using Medis and CVI42 post-processing software. The results of the study showed that the resulting LA εs and LA εe values using CVI42 software were significantly higher than those reported by Medis. The LA εs and LA εe values measured on TTE were significantly lower than those measured by Medis; however, previous studies did not compare the differences in strain rates. Interpretation of these results, application of the cutoff points, and follow-up depend on the model and vendor used to calculate LA strain and the normal reference values and are therefore used cautiously in clinical settings.

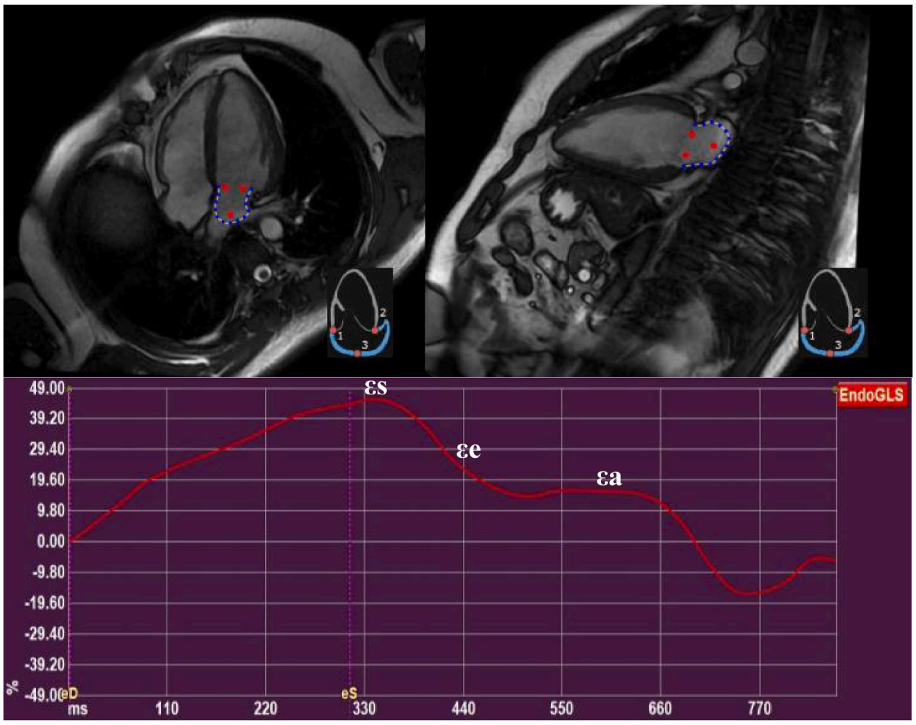
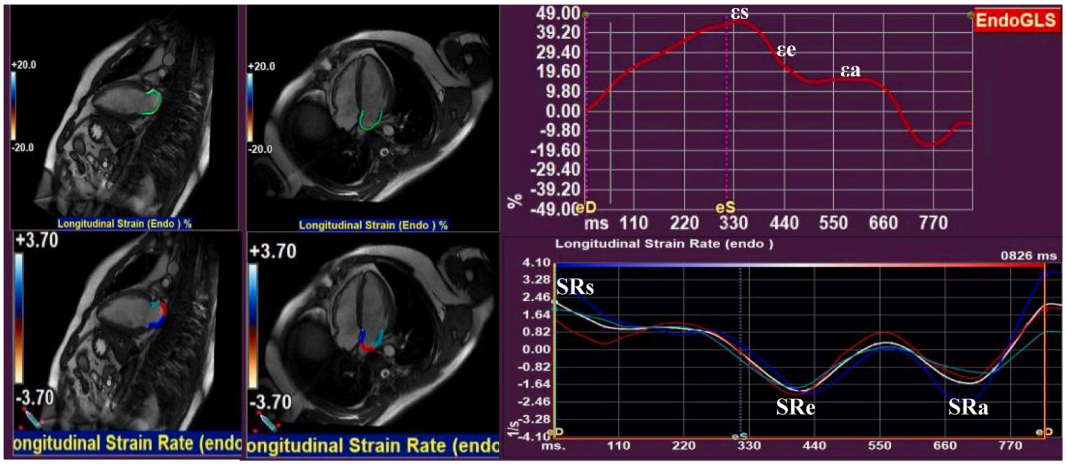


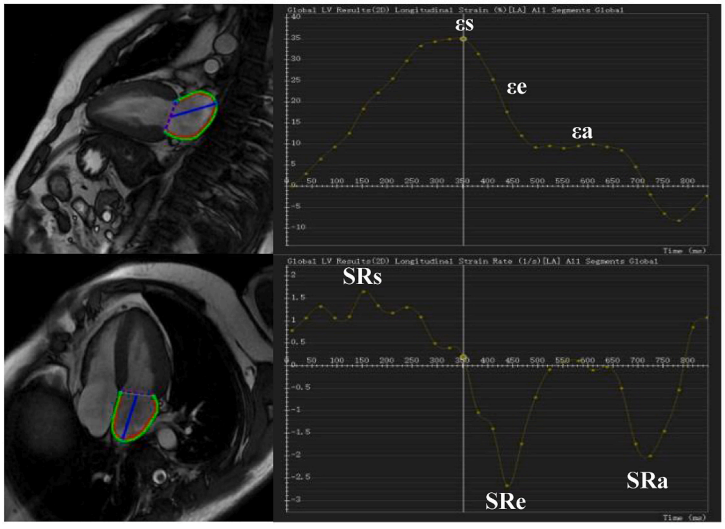
Fig. 1. The pictures show the fast long-axis strain obtained by using the three anatomical reference points in a healthy person.

Table 1
Normal values of strain parameters in LA.

First author	Year	Patients,n	Reservoir function		Conduit function		Booster pump function		CMR Post processing
			εs(%)	SRs(1/s)	εe(%)	SRe(1/s)	εa(%)	SRa(1/s)	
Vien T Truong	2020	112	39.13 ± 9.27	1.93 ± 0.54	25.15 ± 8.34	−2.13 ± 0.69	13.99 ± 4.11	−2.04 ± 0.61	CVI42
Hang Zhou	2022	52	44.7 ± 12.5	1.98 ± 0.51	28.5 ± 8.9	−2.67 ± 0.83	17.2 ± 5.7	−1.99 ± 0.64	CVI42
B.Yao	2023	30	37.81 ± 6.78	1.87 ± 0.41	26.16 ± 6.48	−2.55 ± 0.65	13.05 ± 3.35	−1.85 ± 0.32	CVI42
Yingxia Yang	2020	28	41.5 ± 11.2	1.5 ± 0.4	25.9 ± 10.0	−1.1 ± 0.4	15.6 ± 6.3	−1.0 ± 0.4	Medis
Di Zhou	2022	60	54.1 ± 20.3	1.5 ± 0.4	29.9 ± 15.4	−0.9 ± 0.4	24.2 ± 9.1	−1.1 ± 0.4	Medis
Di Tian	2023	89	32.10 (27.06,37.42)	1.12 ± 0.24	16.00 ± 4.35	−0.98(−1.28,0.81)	16.26 ± 3.20	−1.51 ± 0.33	Medis



(a)



(b)

Fig. 2. Fig. 2a LA strain and strain rate measured using Medis in the same healthy volunteer.εs = 44.3% SRs = 2.4 1/s εe = 29.6% SRe = − 1.5 1/s εa = 14.7% SRa = −1.3 1/s
Fig. 2b LA strain and strain rate measured using CVI 42 in the same healthy volunteer.εs = 35.0% SRs = 1.71/s εe = 26.5% SRe = −2.71/s εa = 8.5% SRa = −2.01/s.

3. Overview of current status of studying LA strain using CMR-FT studies

This article summarizes the current LA strain advantages, research progress, future research prospects, and limitations (see Table 2).

4. Clinical applications

4.1. Value of early evaluation of LA strain

Changes in LA strain are more sensitive in the early stages of cardiovascular disease. It is a more promising indicator for providing clinical significance and predicting early prognosis [6].

LI et al. [16] found that LA strain parameters could be significantly impaired in hypertensive patients before LA dilatation, especially LA εe, which had the highest diagnostic value (AUC = 0.82). Shao et al. [17] studied the myocardial strain in patients with type 2 diabetes mellitus using the CMR-FT technique and found that although the patients had normal LV myocardial strain, significant changes in LA strain occurred. This suggests that LA deformation-related injuries may occur earlier than LV strain changes in

Table 2
Previous studies regarding atrial strain using cardiac magnetic resonance feature tracking.

Type of disease	Advantages and Research Progress of LA Strain	Future Research Directions of LA Strain	Limitations of current LA Strain
Hypertensive cardiology	Early assessment of abnormal cardiac function [16]; assessment of atrial-ventricular coupling injury [6]	Risk stratification for the occurrence of AF and long-term prognostic predictive value	1. The reference ranges of normal values of LA strain and strain rate measured by Medis and CVI42 post-processing software have not yet been standardized, and there is a large variability in the parameters of LA strain compared by TTE. 2. Currently, only two-imensional analyses of LA strain have been performed, with no three-dimensional evaluations, and no analyses of segmental or regional strains. 3. Due to the thin wall of LA, only longitudinal strain measurements of LA have been performed. The potential application value of axial strain is still unclear. 4. The spatial and temporal resolution of CMR images is still low, which affects the accuracy of the measurement results.
Diabetes mellitus	Early assessment of abnormal cardiac function [18]	Whether diuretics prevent, delay, or reverse the injury of LA strain; risk stratification for AF occurrence; long-term prognostic predictive value; assessment of atrial-ventricular coupling injury	
Atrial fibrillation (AF)	Early detection of LA impairment, early identification of diastolic dysfunction [18], improved ability to identify risk of AF [33], indirect quantitative assessment of LA fibrosis, prediction of recurrence of AF after catheter ablation [46], and assessment of long-term and short-term prognosis after catheter ablation for AF [47]	Risk stratification of diastolic dysfunction in AF; effect of pre/post catheter ablation on LA-LV remodeling in PAF; correlation with recurrence of AF and atrial fibrosis	
Myocardial infarction (MI)	Incremental diagnosis of diastolic dysfunction after MI, assessment MACE events and prognostic predictions [34,48,49]	Combination of multi-parameter and prospective large samples for further research	
Hypertrophic cardiomyopathy (HCM)	Detection of LA injury with better sensitivity than volume [5,10,13]; prediction of developing AF [36,37], assessment MACE events and prognostic predictions [5,6,12,13,37,50]	Combination of multi-parameter and prospective large samples for further research	
Dilated cardiomyopathy (DCM)	Incremental prognostic prediction [27], prognostic prediction [51–53], improved risk stratification [38]	Recovery of LA function before and after treatment; assessment of atrial-ventricular coupling injury	
Restrictive cardiomyopathy (RCM)	Prediction of MACE [8]	Early assessment; incremental value, long-term prognostic predictive value	
Myocarditis	Incremental diagnostics, improved diagnostic efficacy [7], best independent predictor of MACE [54]	Confirmation or adjustment of the cutoff point for diagnosis of acute myocarditis and diastolic dysfunction, assessment of atrial-ventricular coupling injury	
Myocardial amyloidosis	Provide incremental value for differential diagnosis of CA and HHD [39]; incremental prognostic prediction [39]; assessment of atrial-ventricular coupling injury [26]; improved risk stratification for AL-CA [39]	Assessment of atrial-ventricular coupling injury	
Left Ventricular Myocardial Noncompaction (LVNC)	Prediction of MACE [55]	Early assessment; incremental value; assessment of atrial-ventricular coupling injury	

(*continued on next page*)

Table 2 (*continued*)

Type of disease	Advantages and Research Progress of LA Strain	Future Research Directions of LA Strain	Limitations of current LA Strain
Aortic stenosis (AS)	Prognostic prediction [58]; provide new insights for reversal of myocardial remodeling and functional recovery in severe AS [59]	Value of incremental assessment after TAVI and prognostic value of long and short-term follow-up after TAVR	
Heart failure (HF)	Early marker of HFpEF LA remodeling [22]; the most critical predictor of diagnosis of HFpEF using exercise stress [56], incremental value of diagnosis of HF [9], improved risk stratification [40] and prognostic prediction of HFrEF [57]	Assessment of atrial-ventricular coupling injury	
Anderson-Fabry disease (AFD)	Early recognition of cardiac involvement and impairment correlates with NativeT1 values, earlier than LV hypertrophy and diastolic dysfunction [23]	Improved risk stratification; prediction of MACE	
Congenital heart disease	In rTOF, early detection of impaired LA function and assessment of atrial-ventricular coupling injury [24]; in rPA/VSD, early detection of diastolic dysfunction [25]	Long- and short-term prognostic predictive value	

subclinical diseases.

Compensation for LA function slows the decline in cardiac output in the early stages of atrial fibrillation (AF). LA volume remains unchanged, although the LA strain may already be impaired. Yamada et al. [18] compared LA strain and function among 106 patients with paroxysmal atrial fibrillation (PAF) and 20 controls and found that the LA reservoir and conduit functions were reduced in the PAF group. LA εa was reduced (11.4 ± 4.3% vs. 15.2 ± 5.6%, p = 0.002) while the LAEFbooster was normal, suggesting that LA strain can identify microscopic pump dysfunction that is undetectable by LA booster ejection fraction in patients with PAF.

Yao et al. [10] quantified LA strain and function in patients with hypertrophic cardiomyopathy (HCM) and hypertension-related left ventricular hypertrophy (LVH) and found that three functions of the LA were impaired in these patients. The LA SRa was reduced in the obstructive HCM group, although the LA booster ejection fraction, which also reflects LA booster function was normal. Hinojar et al. [5] demonstrated impaired LA longitudinal strain in HCM patients with normal LA volume and LV filling pressures. Yang et al. [13] found that LA εs and LA εe were dysfunctional before LA enlargement in patients with NOHCM based on the following results: LA reservoir function (LA εs: 35.0 ± 12.0% vs. 41.5 ± 11.2%, p = 0.03; SRs: 1.3 ± 0.4 1/s vs. 1.5 ± 0.4 1/s, p = 0.02) and conduit function (LA εe: 18.7 ± 7.9% vs. 25.9 ± 10.0%, p < 0.01; SRe: 0.8 ± 0.3 1/s vs. −1.1 ± 0.4 1/s, p < 0.01). These results suggest that LA strain should be more sensitive and earlier than left atrial volume to evaluate atrial dysfunction in HCM patients.

Myocarditis is a major cause of cardiac morbidity and mortality among young athletes [19]. Therefore, early and accurate diagnosis is of great clinical importance. Dick et al. [20] evaluated myocardial strain in 30 patients with myocarditis and found that the LA SRe was the best independent predictor of acute myocarditis (AUC = 0.80), with a diagnostic cutoff value of −1.6 1/s, specificity of 80%, and sensitivity of 83%, suggesting that LA strain parameters improve diagnostic ability in patients with suspected myocarditis. In patients with myocarditis, although the LV ejection fraction is in the normal range in the early stage, the LV diastolic function, which is closely related to LA, has been impaired [21], thus atrial strain analysis helps in early prediction of myocarditis.

CMR-LA strain plays an important role in atrial remodeling in patients with heart failure with preserved ejection fraction (HFpEF). Roeder et al. [22] demonstrated that LA εe is an early marker of LA functional remodeling in patients with HFpEF.

In the absence of LV hypertrophy and diastolic dysfunction (DD), the LA strain is already impaired in patients with Fabry cardiomyopathy, which could be a potential new indicator for recognizing early cardiac involvement [23].

Atrial function and its significance in congenital heart disease remains unclear. Hu et al. [24] evaluated LA strain before LA dilatation in patients with repaired tetralogy of Fallot (rTOF) and found that they had decreased LA strain and strain rates. Ma et al. [25] evaluated LA volume and function in patients with repaired pulmonary artery atresia with ventricular septal defect and found that LA function was already altered with preserved biventricular ejection fraction, which may be an early indication of LV DD.

In summary, LA strain parameters can identify lesions early on and reflect changes in early function in the early stages of cardiovascular diseases.

4.2. Value of incremental diagnostics of LA strain

In patients with myocarditis, the LA strain parameter combined with the 2018 Lake Louise criteria improved the diagnostic efficacy of myocarditis, with LA SRe being the best univariate parameter for diagnosis (AUC = 0.72) [7].

Zhang et al. [26]measured LA and LV myocardial strain to differentiate between hypertensive heart disease (HHD) and CA, both of which cause LVH. LA εs had the highest differential diagnostic efficacy, with an AUC of 0.886, which is higher than that of GLS (AUC = 0.770), suggesting that LA strain can provide incremental value in the differential diagnosis of CA and HHD.

Leng et al. [9] analyzed LA strain in three heart failure (HF) phenotypes and found that fast LA εs was a significant predictor of NT-proBNP, indicating the incremental contribution of fast LA strain in identifying HF. Patients on dialysis with HFpEF, LA εs, LA εe, and SRs showed higher diagnostic value than conventional clinical indicators and echocardiographic parameters (Harrell's C-statistic: 0.83 vs. 0.96, 0.97, and 0.97, respectively; all p < 0.0001) [11]. The incremental diagnostic value of LA strain in patients with HFrEF has also been confirmed. Bo et al. [27] concluded that LA strain and strain rates were significantly lower in patients with ischemic and non-ischemic dilated cardiomyopathy (DCM) with HFrEF.

In summary, LA strain and strain rate have corresponding diagnostic incremental value for different cardiovascular diseases, improving the accuracy of conventional diagnostic models (conventional LA geometry morphology and ultrasound indices).

4.3. Value of LA strain for assessing atrial-ventricular hemodynamics and coupled injury

Under physiologic conditions, the reservoir function, conduit function, and booster pump function of the atria are interdependent and can redistribute among each other [28]. Blood delivery to the LA is critical for the regulation of LV filling and function [29]. Atrial reservoir function reflects atrial relaxation and compliance, which is mainly influenced by ventricular systolic function. Conduit function is mainly dependent on ventricular pumping capacity, which is closely related to changes in ventricular diastolic function and stiffness. Booster pump function regulates ventricular filling and is essential for the maintenance of cardiac output when ventricular diastole is impaired or compliance is reduced [30].

Before significant LV hypertrophy, chronic hypertension-induced pressure-related LV DD can cause LA dysfunction [16]. Zhou et al. [6] demonstrated that impaired LA εs and LA εa were correlated with clinical outcomes at different stages of LA booster dysfunction (p < 0.05) and that LA and LV time-strain curves were strongly correlated throughout the cardiac cycle (r = −0.95, and p < 0.001).

A study comparing LA strain function and LV-ECV in patients with PAF and controls found a correlation between LV-ECV and LA εs and LA εe in patients with PAF suggesting a potential link between LV and LA functional remodeling [18].

Significant correlations between LA strain and LV parameters (GLS and LVEF) in patients with both CA and HHD confirmed that LA

strain reflects LV contractile dysfunction to some extent, with LA εs being the most strongly correlated with LV-GLS and three phases of the LAS being significantly correlated with LV-ECV, further suggesting a potential link between LV and LA function [26].

Hieu et al. [31] measured LA functional indices and LV native T1 values in rTOF patients and found a correlation between higher native T1 values and lower εa:εs GLS ratios with increasing ECV or interstitial fibrosis loads, suggesting deterioration of diastolic function and adverse atrial-ventricular interactions.

In summary, LA strain is a promising biomarker that may be used to assess hemodynamic dysfunction and impaired LA-LV coupling among different diseases and more findings are needed to validate it in the future.

4.4. Value of improving risk stratification of LA strain

LA strain is associated with an increased risk of MACE and can be used in the management of patients to improve risk stratification for cardiovascular disease.

The standard deviation of the time to the peak longitudinal strain (SD-TPS) was significantly higher (39.9 vs. 23.4 ms, $P < 0.001$) in patients with AF with a previous history of stroke or transient ischemic attack (TIA). SD-TPS can identify patients with stroke/TIA more accurately than the CHA2DS2-VASc score alone [32]. LA strain also significantly improved the identification of AF risk in older patients with stroke risk factors; when the LA εa was <17%, the odds of developing AF increased two-fold [33].

LA strain has greater diagnostic value in stratifying the presence and severity of DD [34]. CMR-derived LA εs may play an important role in improving risk stratification after STEMI [35].There was a significant increase in MACE for high-risk groups after STEMI with LA εs below 19.2%. The addition of LA εs to LVEF resulted in a significant increase in AUC from 0.713 for LVEF alone to 0.775.

LA εs (≤18%) and LA εa (≤8%) were associated with a nearly three- and four-fold increased risk of new-onset AF, respectively, even in HCM patients with an LA diameter of <45 mm, and are important determinants of AF risk [36]. In addition, despite a similar degree of DD, the global longitudinal LA strain was more significantly impaired in HCM patients with elevated NT-proBNP and hsTnT levels [37].

Studies of DCM have revealed that LA εe (hazard ratio [HR] = 3.65, $P < 0.001$) is a strong independent prognostic predictor of DCM and that the inclusion of LA εe in the management of patients with DCM should be considered to improve risk stratification [38].

Tan et al. [39] analyzed LA strain parameters in 87 patients with systemic AL amyloidosis based on CMR-FT and found that every unit of decrease in LA εs was associated with a 13.4% increase in the risk of all-cause mortality, in a multivariate model.

PALS≤15% and NTproBNP≥874.5 ng/l provide optimal risk stratification for the composite endpoint in HF patients and can be used as an additional indicator of congestion to optimize therapeutic management [40].

In summary, LA variables should be considered for inclusion in patient disease management to better improve risk stratification for cardiovascular disease.

4.5. Value of LA strain for assessing MACE and prognostic predictions

LA strain is an independent predictor of MACE that provides prognostic predictive value beyond traditional means. LA fibrosis is usually detected by CMR, which is difficult to quantitatively evaluate. However, it can be indirectly reflected through LA strain, which may increase important information about the physiological importance of LA fibrosis and provide important value for predicting atrial fibrillation.

An important feature of AF is atrial remodeling, which can impair LA function [41]. The main effect of AF is on atrial compliance, thereby impairing LA εs and LA εe [42,43]. Hopman [44] and Pisciotti et al. [45] reached similar conclusions: the three strain parameters of the LA were significantly reduced in patients with AF. In addition, Hopman reported that AF with extensive LA fibrosis produced lower LA εs and LA εe and that conduit function correlated most strongly with the degree of LA fibrosis. Gastl et al. [46] reported that impaired LA booster function predicted AF recurrence after ablation, with an AUC of 0.73 ($p = 0.033$). Habibi et al. [47] studied the short- and long-term correlations between AF catheter ablation and LA function in 51 patients with AF using CMR and found that on the second day after ablation, active LA emptying fraction, total LAEF and peak LA strain had decreased. providing additional support for the importance of appropriate perioperative anticoagulation for the prevention of cardiac embolic stroke; in long-term follow-up, patients with recurrent AF showed significantly lower LA total ejection fraction ($33 \pm 3.1\%$ vs. $38 \pm 3.3\%$, $p = 0.0015$) and peak LA strain (18 ± 2.2 % vs. $20 \pm 2.1\%$, $p = 0.047$) values.

LA mechanics are affected by MI. Myocyte necrosis increases LV stiffness, leading to a decrease in LV diastolic filling capacity [34]. Andreas et al. [48] showed that LA εs < 18.8% could be used as an independent predictor of adverse cardiovascular events after acute MI. Leng et al. [49] showed that LA εs < 21.8% or LA εe < 10.5% could be used as an independent predictor of poor prognosis in patients with acute ST-elevation MI (STEMI). Kim et al. [34]combined ultrasound and CMR findings to assess LA strain and concluded that PALS improved the prediction of congestive HF and AF after MI.

The identification of high-risk HCM patients remains challenging. Hinojar et al. [5] found that LA εs occurred in <18% of HCM patients who experienced both primary and secondary endpoints. LA εs and LA εe (HR, 0.94 and 0.89, $p = 0.019$ and 0.006, respectively) were independent predictors of composite adverse events when evaluating the correlation between fast LA-las and adverse clinical outcomes in HCM patients [13,50]. Zhou et al. [6] also found that LA εa was a predictor of the occurrence of adverse endpoint events in HCM patients ($HR = 0.924$, $p = 0.007$). In addition, Tian found that the GLS SR and GCS were also impaired in HCM patients, with LA εa ≤8.9% being the strongest determinant ($HR = 8.9$; 95% CI [1.951, 40.933], $p = 0.005$), providing a predictive value for adverse clinical events ($AUC = 0.86$; 95% CI [0.77–0.98]) that exceeds traditional prognostic predictive values [12]. The LA GLS not only reflects LV DD in HCM patients but also serves as an early predictor of HF and AF risks in HCM patients [37].

Minzat et al. [51] assessed LA geometry and strain using CMR in patients with non-ischemic DCM and concluded that LA εs had significant prognostic predictive power. Another study demonstrated that LA εs and LA εe (HR = 0.95, P = 0.008 and HR = 0.92, P = 0.01, respectively) were independent predictors of all-cause mortality and the primary endpoint of cardiac transplantation in patients with DCM and that these parameters provided increased prognostic value [52]. One study that included 58 patients with severe idiopathic DCM and a median follow-up of 43 months showed that the LA SRs significantly predicted the association with cardiovascular events and were strong prognostic indicators [53].

Regarding restrictive cardiomyopathy, a study found that patients with LA εs <15% (adjusted HR = 5.971, p = 0.005; HR = 4.252, p = 0.001) had all-cause mortality and composite event rates that were six and nearly four times higher, respectively, than those for LA εs >34% [8].

Chen et al. [54] assessed changes in LA and biventricular strain during suspected myocarditis and their prognostic value; the initial SRa was the only significant predictor of MACE at follow-up and could serve as a useful prediction tool for poor outcomes during follow-up.

Han et al. [55] found that LA εs <12.7% was an independent predictor of high-risk HF events (HR = 23.208, P = 0.003) in patients with left ventricular noncompaction cardiomyopathy (LVNC), providing important information for predicting high-risk HF events in patients with LVNC.

A common manifestation of light-chain (AL) amyloidosis is the progression and dysfunction of LA remodeling. Moderate and high amyloid loads (ECV groups II and III) showed progressive impairment in LA strain and strain rates compared with low amyloid loads (ECV group I), and the mortality risk was higher in patients with low (<8.6%) versus high (≥8.6%) LA εs in patients in the ECV group II. LA εs provided independent and incremental prognostic value for all-cause mortality among patients with AL cardiac amyloidosis (CA) [39].

Pastore et al. [40] predicted the congestive status of patients with acute and chronic HF, and found that NT-proBNP level (AUC = 0.87) and global PALS (AUC = 0.82) were good predictors of adverse composite endpoints. Real-time cardiac magnetic resonance exercise stress LA long axis strain was independently associated with HFpEF after adjustment for clinical and imaging measures and emerged as the best predictor for HFpEF (AUC, 0.93; P = 0.029) [56]. Chirinos et al. [57] comprehensively assessed phasic LA function in subjects with HFrEF, HFpEF, and subjects without HF, and found that LA reservoir and conduit function were significantly associated with composite outcomes in patients with HFrEF. LA εe, LA SRe, and LA εs exhibited the strongest correlations.

Cionca et al. [58] evaluated the role of CMR in LA geometry morphology and function in patients with severe aortic stenosis (AS). LA εe <14.5% appeared to be an independent predictor of outcome. Lange et al. [59] evaluated the process of myocardial remodeling in patients with severe AS undergoing transcatheter aortic valve replacement (TAVR) and found that LA functional parameters significantly improved 1 year after TAVR (LA εs [13.3 ± 6.3% to 17.8 ± 6.7%, p = 0.001], LA εe [5.5 ± 3.2% to 8.4 ± 4.6%, p = 0.001], and LA εa [8.2 ± 4.6% to 9.9 ± 4.2%, p = 0.027]). CMR-FT-based atrial strain analysis provides insights into myocardial remodeling reversal and functional recovery in severe AS.

In summary, LA strain analysis plays an important role in predicting the occurrence of MACE and adverse prognosis in various cardiovascular diseases, which may facilitate accurate treatment decisions in the future [27].

5. Expectations

The current review of LA strain using CMR-FT, which mainly included small, single-center studies that focused on AF, HCM, and HF, has some limitations. Future studies on LA strain should focus on (1) standardizing measurement methods and vendor differences to establish normal strain reference values based on sex and age; (2) further software development is needed to facilitate reliable segmental or regional strain analysis; (3) conducting large prospective multicenter, multiparameter, multivendor studies with long-term follow-up periods to explore the potential value of LA strain in additional cardiovascular diseases, to guide clinical application better in the future; and (4) the potential mechanism of impaired LA-LV/RV coupling needs to be validated by incorporating additional cardiovascular disease findings.

6. Conclusion

The CMR-FT-derived LA strain is an emerging parameter with good repeatability and reproducibility for the early detection of LA myocardial injury and comprehensive assessment of functional changes in three temporal phases, which is of great value. Furthermore, CMR-FT-derived LA strain has broad clinical applications for incremental diagnosis, risk stratification, prognostic prediction, and the evaluation of treatment effects for a wide range of cardiovascular diseases.

Ethics approval and consent to participate

Not applicable.

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Data availability statement

Data included in article/supp. material/referenced in article.

CRediT authorship contribution statement

Yetong Zhao: Writing – original draft. **Yang Song:** Supervision. **Xiaolin Mu:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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