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Research article

Diagnostic value of cardiac magnetic resonance imaging-based left atrial strain analysis for identifying cardiac diseases with overlapping phenotype

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ABSTRACT

Background: The main objective of this study was to compare diagnostic accuracies of cardiac magnetic resonance (CMR)-based left atrial (LA) volumetry and function, including LA strain analysis, for the detection of myocardial impairments in diseases of different etiologies such as hypertensive heart disease, Fabry disease and acute myocarditis.

Methods: Healthy volunteers (HV, n = 50) and patients with cardiomyopathies (n = 140), including patients with hypertensive heart disease (n = 40), Fabry disease (n = 49), and acute myocarditis (n = 51), underwent CMR at 3 T. Atrial volume and strain analysis based on long-axis cine acquisition was performed using a commercially available post-processing software.

Results: Patients exhibited impaired LA reservoir (28.60 ± 9.91 % vs. 41.27 ± 7.54 %), conduit (17.35 ± 7.72 % vs. 26.89 ± 5.25 %) and booster strain (11.30 ± 4.52 % vs. 14.61 ± 4.15 %) parameters compared to HV (all $p < 0.001$). In contrast, the volumetric values showed no significant difference between patients and HV ($p > 0.05$). Passive and total emptying fractions were significantly lower in patients ($p < 0.001$), while active emptying fraction did not differ ($p > 0.05$). Superior diagnostic accuracy for the LA reservoir strain demonstrated improved prognostic performance comparing to LA volumetric and functional parameters (area under the curve [AUC] 0.85 vs. e.g. passive emptying fraction AUC 0.78, $p < 0.05$).

Conclusion: LA strain parameters effectively distinguish patients with cardiac diseases presenting overlapping phenotypes from HV and outperform volumetric and traditional functional assessments of the LA.

1. Introduction

In recent years, the importance of quantifying atrial function and volumes in cardiomyopathies for diagnostic and prognostic purposes has been increasingly recognized. Left atrial (LA) size, volume, and functional parameters are linked to adverse clinical outcomes in cardiomyopathy patients [1,2,3]. However, LA contraction follows a complex sequence, which is not sufficiently described by volumes and conventional functional parameters alone [1,4]. LA contraction can be divided into three phases: (1) reservoir function for collecting blood from pulmonary veins during ventricular systole; (2) conduit function, a passive filling phase during early ventricular diastole, and (3) booster function by atrial active contraction to increase ventricular filling during late diastole [5,6]. Analyzing LA deformation may better represent these phases, thus overcome the limits of volumetric assessment, such as the reliance on geometric presumptions by utilizing the biplane area length

Abbreviations: AEF, active emptying fraction; AF, atrial fibrillation; AM, acute myocarditis; AUC, area under the curve; BSA, body surface area; CMR, cardiac magnetic resonance imaging; CMR-FT, cardiac magnetic resonance – feature tracking; ECG, electrocardiogram; EF, ejection fraction; FD, Fabry disease; FOV, field of view; HHD, hypertensive heart disease; HV, healthy volunteers; LA, left atrial/atrium; LV, left ventricle; MaxLA-Vol., maximal left atrial volume; MinLA-Vol., minimal left atrial volume; PEF, passive emptying fraction; ROC, receiver operating characteristic; RV, right ventricle; SCMR, Society for Cardiovascular Magnetic Resonance; SSFP, steady-state free precession; TE, echo time; TEF, total emptying fraction; TR, repetition time.

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method [1]. In addition, LA strain abnormalities can be detected despite normal LA size, rendering LA strain as a sensitive marker to recognize early left ventricular (LV) diastolic dysfunction [7,8].

Clinically, evaluation of atrial volume and function is often performed using echocardiography, which has several limitations, including high interobserver variability and the possibility of a suboptimal field of view [7]. Cardiac magnetic resonance imaging (CMR) by contrast is known for its good accuracy respectively reproducibility and is the current gold-standard in the non-invasive assessment for the evaluation of atrioventricular volumes and function [9,10]. Furthermore, CMR has the benefit of high spatial resolution and clearer visualization of atrial endocardial borders [11]. Recent focus on CMR-strain analysis highlights the growing recognition of advanced CMR feature tracking (CMR-FT) as a reliable technique for assessing atrial function through strain imaging.

We hypothesized that LA strain imaging provides a more effective method than conventional volumetric and functional analysis for detecting acute and chronic cardiac diseases such as hypertensive heart disease, Fabry disease, and acute myocarditis.

The main objective of this study was to compare diagnostic accuracies of CMR-based LA volumetry and function with LA strain analysis and to investigate LA strain as a diagnostic marker in phenotypes with overlapping imaging features but different pathophysiological backgrounds and mechanisms of impaired LA function.

2. Methods

The protocol of this cross-sectional single-center study was approved by the responsible institutional ethics committee (837.196.13 (8881-F)) with a waiver for informed consent for the retrospective assessment of all patient data. All healthy volunteers (HV) provided written informed consent.

2.1. Study population

For this retrospective study, the institutional database was searched for patients with selected chronic and acute cardiomyopathies who underwent CMR from 2013 to 2019. This led to a total of 166 patients, categorized into subgroups comprising individuals diagnosed of myocardial diseases of different etiologies such as hypertensive heart disease (HHD, n = 46), Fabry disease (FD, n = 65) and acute myocarditis (AM, n = 55). In accordance with the current guidelines [12], the respective clinical diagnoses of HHD and AM were confirmed using clinical data, echocardiography and CMR. The diagnosis of FD was additionally confirmed through genotype analysis **(Table S1)**.

Additionally, a prospectively recruited cohort of 52 HV, who had previously been enrolled as a cohort to establish local reference values for T1 mapping, served as a control group. Inclusion criteria for the prospectively enrolled HV were no history of cardiovascular events or symptoms, no cardiovascular risk factors (e.g., diabetes or hypertension), and normal cardiac dimensions as judged by CMR.

After initial screening, a total of 28 subjects were excluded due to poor image quality, artefacts, or an incomplete cardiac cycle, rendering strain analysis not feasible. Thus, a total of 190 subjects (HHD (n = 40), FD (n = 49), AM (n = 51) and HV (n = 50)) were included in the final analysis.

2.2. Image acquisition

All patients underwent CMR at 3 Tesla (MAGNETOM Prisma or Skyra, Siemens Healthineers, Erlangen, Germany) following the same institutional imaging protocol throughout the study period, thus minimizing inter-scanner variability. Standard cardiac views (2-, 3-, and 4-chamber) were acquired using a unified imaging protocol comprising a conventional balanced steady-state free-precession cine sequence with retrospective electrocardiography (ECG) gating and standard parallel imaging acceleration (GeneRalized Autocalibrating Partial Parallel Acquisition, GRAPPA 3). Typical pulse sequence parameters were as follows: repetition time (TR) 3.88 ms; echo time (TE) 1.42 ms; reconstructed cardiac phases 25; field of view (FOV) 360 mm; flip angle 60°; and voxel-size 1.5 × 1.5 × 8.0 mm.

2.3. Image analysis and post-processing

A dedicated cardiovascular post-processing software (cvi42 Circle®, v5.11, Circle Cardiovascular Imaging, Calgary, Canada) was used for the analysis of all cine sequences following guidelines by the Society for Cardiovascular Magnetic Resonance (SCMR) [13]. LA volumes and functions were semi-automatically assessed by LA time-volume curves. Minimal and maximum LA volumes were assessed applying the biplane area-length calculation technique using the 2- and 4-chamber views of the LA [14]. LA volumes were indexed to body surface area (BSA) [15]. Active emptying fraction (AEF), passive emptying fraction (PEF), and total emptying fraction (TEF) were computed by utilizing the time-volume curves and the subsequent equations:

$$\text{AEF} = 100\% \times \frac{\text{Mid-diastolic Vmax} - \text{Vmin}}{\text{Mid-diastolic Vmax}}$$

$$\text{PEF} = 100\% \times \frac{\text{Vmax} - \text{Mid-diastolic Vmin}}{\text{Vmax}}$$

$$\text{TEF} = 100\% \times \frac{\text{Vmax} - \text{Vmin}}{\text{Vmax}}$$

From a physiological perspective, AEF reflects the atrial booster function, while PEF represents conduit function, and TEF characterizes the reservoir function of the atria [16,17].

In all acquired images, LA strain analysis was conducted semi-automatically at end-diastole in the 2-, 3-, and 4-chamber views. The endo- and epicardial borders of the LA were manually traced on a single phase of the cine images during the ventricular diastole (Fig. 1). Subsequently, employing an automated computation, the software algorithm tracked myocardial borders throughout the cardiac cycle. Visual validation ensured the quality of tracking and contouring, with manual corrections if necessary [9]. Conforming to standard practice, the orifices of the pulmonary veins, and the atrial appendage were excluded [18,19]. Ultimately, the software autonomously calculated the longitudinal atrial strain. Using the LV end-diastolic phase as a zero-reference, strain curves were generated to identify peaks corresponding to the LA contraction phases of the cardiac cycle (Fig. 1) [20,21]. In the following process, all strain parameters were calculated from the numeric raw data rather than extracted from the strain curves.

2.4. Statistical analysis

All statistical analyses were performed using SPSS Statistics (IBM Corp. Released 2020. IBM SPSS Statistics for Windows, Version 27.0. Armonk, NY: IBM Corp) and MedCalc (MedCalc Software bv, Ostend, Belgium; https://www.medcalc.org; 2020, Version 22.007). The Kolmogorov-Smirnov test with Lilliefors correction was used to assess the normality of continuous variables. Independent t-tests were used to identify differences between the groups if the data was normally distributed. If not, the differences were tested with the Mann-Whitney *U* test. Receiver operating characteristic (ROC) curve analyses were used to calculate areas under the curve (AUC). To further evaluate diagnostic accuracies, sensitivity/specificity were calculated, and optimal cut-offs were determined by means of highest Youden's Index. The DeLong method was used to conduct pairwise comparisons of ROC curves, aiming to determine significant differences between AUCs. The significance level was set at $p < 0.05$.

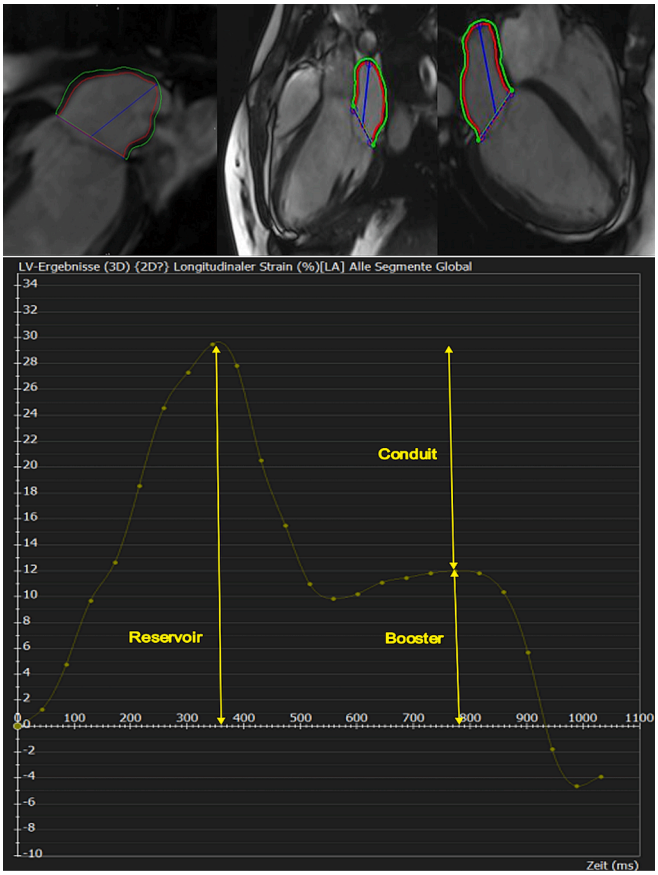

Fig. 1. Semiautomatically derived contours of the left atrium in 2- (left upper), 3- (middle upper), and 4-chamber views (right upper) and derived left atrial strain curve (lower) with reservoir, conduit and booster strain in a patient with Fabry disease.

3. Results

3.1. Study population

The overall study population consisted of 190 subjects (67 (35.26 %) female, mean age 40.8 ± 17.7 years). This included 140 patients (42 (30 %) female, mean age 44.6 ± 17.9 years) and 50 HV (25 (50 %) female, mean age 26.6 ± 5.1 years). Further detailed baseline characteristics of the study population can be found in Table 1.

Table 1
Baseline characteristics, volumetric, functional and strain parameters (Patients vs. HV). *HV*: healthy volunteers, *BMI:* body mass index, *BSA*: body surface area, *MinLA-Vol.*: minimal atrial volume, *MaxLA-Vol.*: maximal left atrial volume, *AEF*: active emptying fraction, *PEF*: passive emptying fraction, *TEF*: total emptying fraction, LA: left atrial.

	Patients (n = 140)	HV (n = 50)
Female (n, %)	42 (30)	25 (50)
Age (years)	44.60 ± 17.2[#]	26.60 ± 5.05
BMI (kg/m^2)	26.60 ± 5.09[#]	22.82 ± 2.75
BSA (m^2)	1.99 ± 0.27[#]	1.85 ± 0.22
MinLA-Vol. (ml)	27.94 ± 16.78	24.07 ± 8.84
MaxLA-Vol. (ml)	69.15 ± 25.57	75.96 ± 20.21
AEF (%)	41.82 ± 11.44	44.26 ± 9.56
PEF (%)	43.08 ± 14.31[#]	56.56 ± 10.26
TEF (%)	61.47 ± 10.94[#]	68.92 ± 6.17
LA Reservoir (%)	28.60 ± 9.91[#]	41.27 ± 7.54
LA Conduit (%)	17.35 ± 7.72[#]	26.89 ± 5.25
LA Booster (%)	11.30 ± 4.52[#]	14.61 ± 4.15

[#]statistically significant differences between patients and HV

3.2. Patients vs. HV

Comparing the atrial volumetric parameters of the total cohort of patients with acute and chronic cardiac diseases such as HHD, FD and AM to HV, no significant differences were detected (e.g. MinLA-Vol. 27.94 ± 16.78 ml vs. 24.07 ± 8.84 ml, $p = 0.33$). Regarding the emptying fractions, significantly lower values were found for TEF and PEF (e.g. PEF 43.08 ± 14.31 % vs. 56.56 ± 10.26 %, $p < 0.001$). In comparison, no statistically significant difference was observed for AEF (41.82 ± 11.44 % & vs. 44.26 ± 9.56 %, $p = 0.20$) when comparing the patient's cohort and HV subjects.

LA strain analysis revealed significantly lower values in all phasic function parameters in the patient's cohort opposed to HV (LA reservoir strain 28.60 ± 9.91 % vs. 41.27 ± 7.54 %, $p < 0.001$; LA conduit strain 17.35 ± 7.72 % vs. 26.89 ± 5.25 %, $p < 0.001$; and LA booster strain 11.30 ± 4.52 % vs. 14.61 ± 4.15 %, $p < 0.001$) (**Fig. S1,** Table 1**)**.

The LA reservoir and conduit strain had the highest discriminatory power between the patient's group and HV with an AUC of 0.85 and 0.84, respectively. This led to a sensitivity of 80.9 % and a specificity of 82.0 % for LA reservoir and 78.0 %/81.6 % for LA conduit strain. In comparison of the ROC-curves, all strain parameters outperformed volumetric parameters ($p < 0.05$) (Fig. 2**,** Table 2).

3.3. Subgroup analysis

3.3.1. Patients with hypertensive heart disease (HHD)

LA strain analysis revealed significantly lower values in HHD patients compared to controls in all phasic function parameters (LA reservoir strain 21.84 ± 8.38 % vs. 41.27 ± 7.54 %, $p < 0.001$; LA conduit strain 11.48 ± 5.71 % vs. 26.89 ± 5.25 %, $p < 0.001$; and LA booster strain 10.27 ± 4.74 % vs. 14.61 ± 4.15 %, $p < 0.001$).For HHD patients, the LA conduit strain showed the highest discriminatory accuracy with an AUC of 1.00, leading to a sensitivity of 95.7 % and a specificity of 100.0 %. Comparing the AUCs of strain and volumetric parameters showed superior performance of the LA conduit and reservoir strains compared to the clinical standard of volumetric parameters minimal and maximal LA volume ($p < 0.001$).

3.3.2. Patients with Fabry disease (FD)

The evaluation of LA strains revealed significantly lower values for patients with FD compared to HV (LA reservoir strain 32.82 ± 10.17 % vs. 41.27 ± 7.54 %, $p < 0.001$; and LA conduit strain 20.62 ± 7.70 % vs. 26.89 ± 5.25 %, $p < 0.001$). LA booster strain did not differ significantly (12.79 ± 5.06 % vs. 14.61 ± 4.15 %, $p = 0.054$). The ROC-curve analysis of the LA indicated that LA conduit strain had the highest discriminatory power between the groups with an AUC of 0.76, leading to a sensitivity of 80.9 % and a specificity of 71.1 %. There was no evidence of a difference between the AUC of reservoir and conduit strains and the minimal and maximal LA volume parameters ($p > 0.05$).

3.3.3. Patients with acute myocarditis (AM)

In AM patients LA strain analysis showed significantly lower values compared to HV in all phasic function parameters (LA reservoir strain 30.12 ± 7.87 % vs. 41.27 ± 7.54 %, $p < 0.001$; LA conduit strain 19.04 ± 6.51 % vs. 26.89 ± 5.25 %, $p < 0.001$; and LA booster strain 10.71 ± 3.34 % vs. 14.61 ± 4.15 %, $p < 0.001$). ROC-curve analysis concerning the LA demonstrated that LA reservoir strain had the highest discriminatory power between AM patients and HV with an AUC of 0.85, leading to a sensitivity of 80.9 % and a specificity of 82.0 %. The results of the DeLong test revealed significant differences between the LA conduit and reservoir strain, and the minimal and maximal LA volume parameters ($p \leq 0.002$).

Detailed results of the subgroup analysis are shown in Table 3 and 4 as well as Fig. 2 and **S2.**

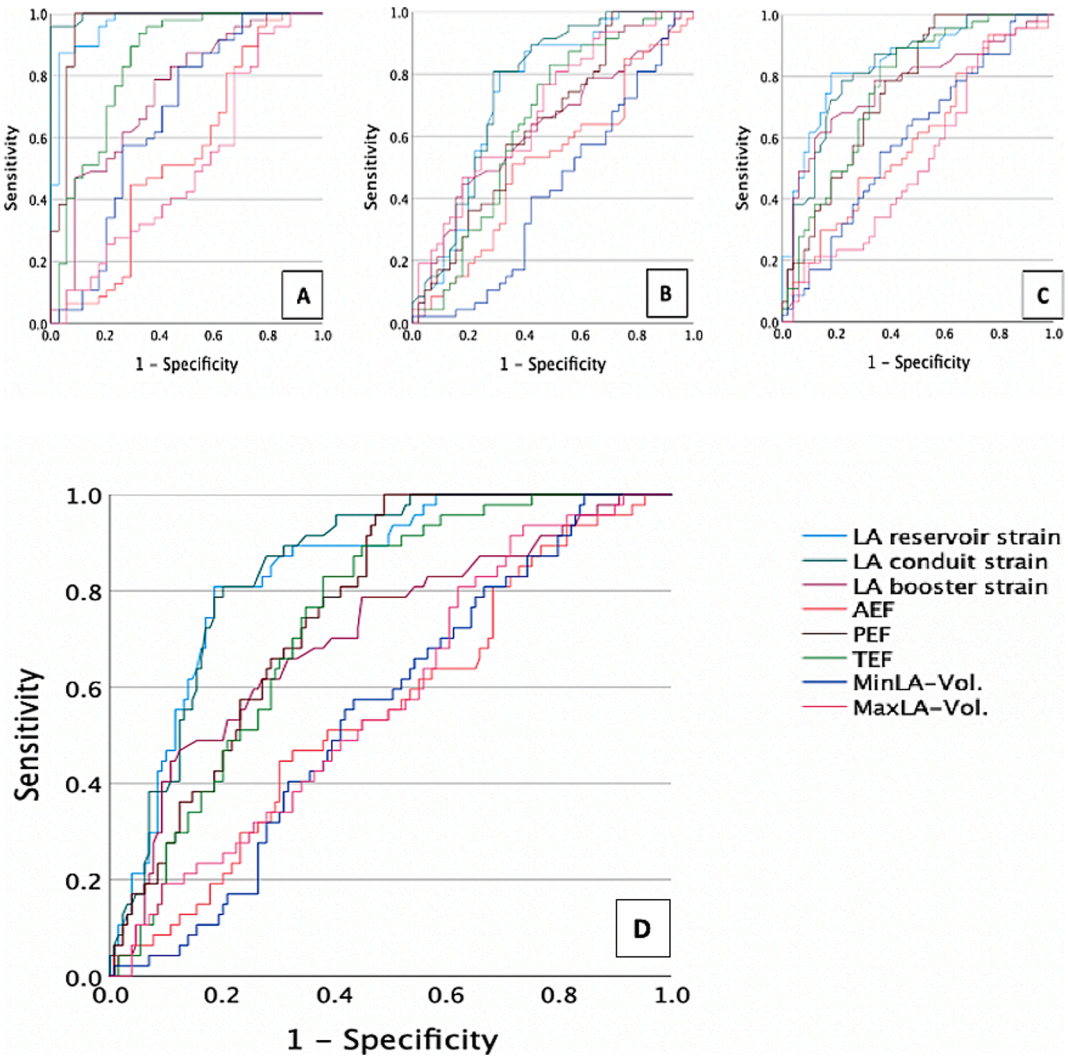

Fig. 2. ROC curves for the volumetric and functional approaches in comparison to LA strain parameters in differentiating HV from patients with HHD (A), FD (B) and AM (C) respectively in differentiating HV from patients with acute and chronic cardiac diseases, including HHD, FD and AM (D). *ROC*: receiver operating characteristic, *LA*: left atrial, *AEF*: active emptying fraction, *PEF*: passive emptying fraction, *TEF*: total emptying fraction, *MinLA-Vol*: minimal left atrial volume, *MaxLA-Vol*: maximal left atrial volume.

Table 2
Comparison of the ROC-curve analysis (Patients vs. HV). *HV*: healthy volunteers, *LA*: left atrial, *MinLA-Vol.*: minimal left atrial volume, *MaxLA-Vol.*: maximal left atrial volume, *AEF*: active emptying fraction, *PEF*: passive emptying fraction, *TEF*: total emptying fraction.

	AUC	Sensitivity (%)	Specificity (%)
LA reservoir	0.85*	80.9	82.0
LA conduit	0.84*	78.0	81.6
LA booster	0.72*	73.8	61.2
AEF	0.56	70.3	45.9
PEF	0.78	51.6	100.0
TEF	0.73	60.9	83.3
MinLA-Vol.	0.55	14.5	100.0
MaxLA-Vol.	0.58	30.4	91.7

*statistically significant difference compared to MinLA-Vol. + MaxLA-Vol.

4. Discussion

This study evaluated the diagnostic value of LA strain analysis using CMR for detecting myocardial dysfunction in various conditions, including hypertensive heart disease, Fabry disease and acute myocarditis. The main findings can be summarized as follows: (1) LA strain, especially reservoir and conduit strain, are significantly impaired in patients with acute or chronic cardiac diseases compared to healthy volunteers, (2) LA strain analysis had superior diagnostic accuracy compared to the clinical standard of volumetric and functional atrial assessment, and (3) LA strain analysis showed abnormalities even in the absence of atrial enlargement.

4.1. Clinical utility of atrial assessment

In recent years, there has been an increasing recognition of the clinical importance of atrial imaging and the utilization of advanced cardiac imaging techniques to assess atrial function. The LA plays a crucial role in cardiac performance and its size is widely regarded as a key indicator of adverse cardiovascular events [2,22,23]. Nevertheless, the mere presence of LA enlargement does not provide a comprehensive understanding of LA function throughout the cardiac cycle. Therefore, several studies have investigated functional atrial parameters such as the AEF, PEF, and TEF for their potential effectiveness in predicting outcomes, e.g. among patients with diastolic dysfunction and in diagnosing and managing atrial fibrillation (AF) [24,25].

The analysis of atrial strain parameters introduces another level of sophistication into the assessment of overall atrial function. Generally

Table 3
Baseline characteristics; volumetric, functional and strain parameters (Subgroups vs. HV). *HHD*: hypertensive heart disease, *FD*: Fabry disease, *AM*: acute myocarditis, *HV*: healthy volunteers, *BMI*: body mass index, *BSA*: body surface area, *MinLA-Vol.*: minimal left atrial volume, *MaxLA-Vol.*: maximal left atrial volume, *AEF*: active emptying fraction, *PEF*: passive emptying fraction, *TEF*: total emptying fraction, LA: left atrial.

	HHD (n = 40)	FD (n = 49)	AM (n = 51)	HV (n = 50)
Female (n, %)	9 (22.5)	24 (48.98)	9 (17.65)	25 (50)
Age (years)	58.85 ± 12.82	38.67 ± 14.95	38.37 ± 15.67	26.60 ± 5.05
BMI (kg/m^2)	28.96 ± 4.40$^{\#}$	23.74 ± 4.67	27.34 ± 4.80§	22.82 ± 2.75
BSA (m^2)	2.09 ± 0.25$^{\#}$	1.81 ± 0.25	2.06 ± 0.23§	1.85 ± 0.22
MinLA-Vol. (ml)	33.61 ± 23.70$^{\#}$	23.28 ± 17.27	28.46 ± 11.88§	24.07 ± 8.84
MaxLA-Vol. (ml)	74.06 ± 30.69	59.85 ± 25.66*	72.41 ± 22.85	75.96 ± 20.21
AEF (%)	41.18 ± 16.73	43.52 ± 9.04	40.76 ± 8.79	44.26 ± 9.56
PEF (%)	31.46 ± 10.29$^{\#}$	50.50 ± 13.85*	44.29 ± 12.12§	56.56 ± 10.26
TEF (%)	57.08 ± 13.40$^{\#}$	63.95 ± 10.41*	61.11 ± 8.21§	68.92 ± 6.17
LA Reservoir (%)	21.84 ± 8.38$^{\#}$	32.82 ± 10.17*	30.12 ± 7.87§	41.27 ± 7.54
LA Conduit (%)	11.48 ± 5.71$^{\#}$	20.62 ± 7.70*	19.04 ± 6.51§	26.89 ± 5.25
LA Booster (%)	10.27 ± 4.74$^{\#}$	12.79 ± 5.06	10.71 ± 3.34§	14.61 ± 4.15

$^{\#}$statistically significant differences between HV and HHD, *statistically significant differences between HV and FD, §statistically significant differences between HV and AM

spoken, LA strain has been suggested as a non-invasive tool for early prognosis and diagnosis, e.g. to assess diastolic dysfunction including correlations with fibrosis and remodeling, surpassing the assessment of LA size alone [3,26]. The incremental prognostic role of LA reservoir strain over conventional LA volume for predicting outcome has been demonstrated recently in various clinical settings [27,28,29,30]. Additionally, evidence of LA remodeling, indicated by impaired LA reservoir strain, even in cases where LA size appears normal, has been observed in cardiometabolic diseases such as hypertension [26].

Specifically, in FD, LA strain measured by CMR can reveal early impairment of atrial function due to myocardial fibrosis and remodeling, even in the absence of overt systolic dysfunction. Conversely, HHD is typically associated with increased LA stiffness and reduced strain as a result of chronic pressure overload, although the specific pattern of strain alteration differs from that observed in FD. In AM, pronounced abnormalities in LA strain are often observed during the acute inflammatory phase, with these changes showing reversibility as the condition resolves. By quantifying LA strain, CMR thus enables the detection of these nuanced differences, thereby supporting more precise subtype differentiation and facilitating the early diagnosis of conditions such as FD, which may otherwise be challenging to identify in their initial stages.

Moreover, enhancing the capability to distinguish between HV and individuals with disease without relying on contrast agents can reduce the invasiveness and duration of CMR scans by altering protocol workflows. Recent studies have highlighted the potential of streamlined protocols for patients with high negative predictive values, demonstrating that acquiring only a few key CMR parameters may suffice. These patients derived no additional benefit from extended CMR examinations, leading to significant reductions in scan time [24,31].

Thus, there is a growing body of evidence that sheds light on the potential of LA strain analysis as a supplemental tool in various cardiovascular diseases.

4.2. Diagnostic accuracies

The main objective of this study was to compare diagnostic accuracies of LA function and volumes with LA strain analysis in a study sample of patients with HHD, FD and AM compared to HV. These cardiac diseases have different pathophysiological backgrounds but may have overlapping imaging features including ventricular hypertrophy.

Prior research has investigated the diagnostic utility of atrial strain analysis using CMR-FT and explored whether it offers improved outcomes compared to volumetric and functional assessments for certain diseases [32,33,34]. Some studies on patients with HHD showed similar results compared to our findings [32,35]. *Wen et al.*, for example, demonstrated that LA strain parameters may exhibit enhanced sensitivity in reflecting LA function impairment compared to LA ejection fraction, including AEF, PEF and TEF in a cohort of hypertensive patients. Furthermore, they demonstrated that both LA reservoir and conduit functions were compromised in patients with hypertension [33]. In a study of patients with hypertrophic cardiomyopathy, *Yang et al.* were able to demonstrate that impairment of LA reservoir and conduit functions occurs even prior to LA enlargement, despite different pathophysiological background for the hypertrophy [34].

Moreover, atrial strain using CMR-FT is a valuable tool for early detection of cardiac involvement in patients with cardiomyopathy associated with FD [7]. In line with the present study, *Halfmann et al.*, who investigated the correlation between LA strain and the severity of cardiac involvement in FD patients, demonstrated impaired strain parameters in a FD patient population [9]. Particularly, the diminished reservoir function of the LA was identified as the most accurate predictor of cardiac involvement. Its unique characteristics and correlation with the cardiac cycle suggest a strong dependency on atrial mechanics, indicating a high sensitivity for detecting diastolic dysfunction [36]. Additionally, the strain parameters, particularly reservoir strain, have previously been observed to outperform volumetric assessments in distinguishing patients with FD from HV [9]. While our study also

Table 4
Comparison of the ROC-curve analysis (Subgroups vs. HV). *ROC*: receiver operating characteristic, *HHD*: hypertensive heart disease, *FD*: Fabry disease, *AM*: acute myocarditis, *HV*: healthy volunteers, *AUC*: area under the curve, *LA*: left atrial, *AEF*: active emptying fraction, *PEF*: passive emptying fraction, *TEF*: total emptying fraction, *MinLA-Vol.*: minimal left atrial volume, *MaxLA-Vol.*: maximal left atrial volume.

	HHD vs. HV				**FD vs. HV**				**AM vs. HV**			
	AUC	Sens (%)	Spec (%)	Cut-Off (%)	AUC	Sens (%)	Spec (%)	Cut-Off (%)	AUC	Sens (%)	Spec (%)	Cut-Off (%)
LA reservoir	0.96*	95.2	88.0	≤ 33.5	0.75	66.7	82.0	≤ 32.8	0.86*	82.4	82.0	≤ 36.3
LA conduit	0.97*	90.5	95.9	≤ 17.8	0.76	66.7	81.6	≤ 22.8	0.84*	74.5	81.6	≤ 22.8
LA booster	0.76*	61.9	79.6	≤ 11.2	0.63	83.3	42.9	≤ 15.9	0.77*	65.3	82.4	≤ 13.3
AEF	0.55	23.5	95.8	≤ 30.1	0.53	65.9	52.1	≤ 44.5	0.60	72.0	47.9	≤ 45.6
PEF	0.95	91.2	100.0	≤ 41.5	0.65	29.6	100.0	≤ 41.0	0.76	44.0	100.0	≤ 41.8
TEF	0.78	64.3	89.6	≤ 62.0	0.65	83.3	51.1	≤ 63.7	0.77	58.8	89.6	≤ 62.0
MinLA-Vol.	0.62	45.2	83.3	≤ 33.8	0.57	81.3	40.0	≤ 17.9	0.60	62.8	56.3	≤ 23.7
MaxLA-Vol.	0.54	31.0	93.8	≤ 52.6	0.66	75.0	51.1	≤ 52.8	0.53	27.5	91.7	≤ 54.1

*statistically significant difference compared to MinLA-Vol. + MaxLA-Vol.

demonstrated that LA reservoir and conduit strain had the best discriminatory accuracy in this cohort of patients, these results did not reach statistical significance in the DeLong test when compared to volumetric parameters. This discrepancy may be attributed to the fact that patients within this group were at different stages of a disease continuum of FD, thus diluting mean differences.

The study situation regarding AM remains scarce. Regarding our investigation of the AM cohort, the findings align with a study conducted by *Dick et al* [37]. They demonstrated impaired reservoir and conduit strains in the LA among AM patients, making it a potential marker for biventricular diastolic dysfunction. However, in contrast to our findings, the study by *Dick et al.* reported preserved booster strain [37]. In a more recent study, *Lee et al.* showed that LA reservoir and conduit strain were lower in AM patients compared to HV and that both parameters independently predict the clinical outcome of these patients [38].

Two potential mechanisms account for the reduction in strain parameters. First, individuals with cardiomyopathy may develop increased wall stiffness caused by LA fibrosis, leading to decreased LA compliance and consequently impaired LA strain. Second, these patients may undergo progressive LA remodeling and dysfunction [3]. As mentioned above, some studies have shown significant differences for LA reservoir and conduit strains, but not for LA booster strain [34,37,39]. These observations suggest that LA reservoir and conduit function gradually decline as LV diastolic dysfunction progresses, while impairment of the booster function may occur at a later stage [33]. A plausible rationale for this variance is that the sustained LA pumping function serves as a compensatory mechanism to uphold stroke volume and LV filling [3].

Moreover, the Frank-Starling mechanism helps provide a further reasonable explanation for these findings, as adaptive redistribution likely takes place in response to hemodynamic changes to ensure proper LV filling and maintain cardiac function during the progression of LV diastolic dysfunction. However, this compensatory effect has limitations, and eventually, decompensation can also lead to a decrease in active LA function [33].

4.3. Limitations

This study has several limitations. First, this is a single-center, retrospective study which may have resulted in selection bias. Additionally, the disease cohorts analyzed in this study were heterogeneous. Second, the study includes a limited number of healthy controls and focuses on a rare disease such as FD, which might impact generalization of the findings. Third, despite several studies that have validated the reproducibility of atrial strain analysis, significant differences still exist between different vendors and there is currently no established reference standard. For image analysis, we utilized a single software primarily designed for the registration of ventricular deformation and it is therefore important to note that the results obtained may not be generalizable to other available software. Fourth, given the retrospective nature, it was outside the scope of the study to provide data on patient-specific outcomes or predict disease progression. Therefore, further studies are required to investigate the relationship between pathological atrial strain values and the progression of the examined diseases. Fifth, while previous studies have shown agreement between speckle-tracking echocardiography and CMR-derived LA strain, we did not compare our findings with echocardiographic results. Sixth, we are aware of the gender bias within this study for HHD and AM, which is due to the retrospective nature. Therefore, findings will have to be prospectively confirmed. Seventh, we are aware of the notably younger age of the HV, which were recruited prospectively. The reported normal values were within one standard deviation of normal LA strain values reported in prior studies with significantly older study samples [40]. Eighth, there is potential for bias due to time-related variations within CMR acquisition parameters, but we have minimized it by ensuring strict adherence to imaging protocols, scanner consistency, reproducibility testing, and uniform post-processing methods. Lastly, while the results do encourage further studies on the supporting role of atrial strain assessment in the diagnostic workflow, the authors acknowledge that the distinction between the different cardiac etiologies in this study based upon strain parameters is a hypothetical scenario owed to the exploratory nature of the study.

5. Conclusion

LA strain parameters, particularly reservoir and conduit strain, effectively distinguish cardiomyopathy and HHD patients from HV. Compared to traditional volumetric and functional atrial assessments, LA strain detects abnormalities even without LA enlargement. Notably, CMR-FT-derived LA strain demonstrates consistent impairment across acute and chronic cardiac diseases, including HHD, FD and AM, highlighting its potential as a supplementary diagnostic tool for diverse myocardial conditions.

CRediT authorship contribution statement

Constantin Reichardt: Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **Maximilian Moos:** Writing – review & editing. **Tilman Emrich:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization. **Karl-Friedrich Kreitner:** Writing – review & editing. **Lukas Müller:** Writing – review & editing. **Lukas Hobohm:** Writing – review & editing. **Tobias Bäuerle:** Writing – review & editing. **Akos Varga-Szemes:** Writing – review & editing. **Moritz C. Halfmann:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Tilman Emrich reports a relationship with Siemens Healthineers AG that includes: board membership, speaking and lecture fees, and travel reimbursement. Tilman Emrich reports a relationship with Circle Cardiovascular Imaging Inc that includes: consulting or advisory. Maximilian Moos reports a relationship with Siemens Healthineers AG that includes: funding grants. Karl-Friedrich Kreitner reports a relationship with Siemens Healthineers AG that includes: funding grants. Lukas Mueller reports a relationship with Siemens Healthineers AG that includes: funding grants. Tobias Baeuerle reports a relationship with Siemens Healthineers AG that includes: funding grants. Akos Varga-Szemes reports a relationship with Siemens Healthineers AG that includes: board membership, speaking and lecture fees, and travel reimbursement. Akos Varga-Szemes reports a relationship with Circle Cardiovascular Imaging Inc that includes: consulting or advisory. Akos Varga-Szemes reports a relationship with Elucid Bioimaging that includes: consulting or advisory and equity or stocks. Moritz C. Halfmann reports a relationship with Siemens Healthineers AG that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejrad.2025.112153.

References

[1] A. Alfuhied, B.A. Marrow, S. Elfawal, G.S. Gulsin, M.P. Graham-Brown, C. D. Steadman, et al., Reproducibility of left atrial function using cardiac magnetic resonance imaging, Eur. Radiol. 31 (5) (2021) 2788–2797, https://doi.org/10.1007/s00330-020-07399-z.

[2] Y. Li, Y. Xu, S. Tang, X. Jiang, W. Li, J. Guo, et al., Left atrial function predicts outcome in dilated cardiomyopathy: fast long-axis strain analysis derived from MRI, Radiology 302 (1) (2022) 72–81, https://doi.org/10.1148/radiol.2021210801.
[3] D. Tian, J. Zhang, Y. He, Z. Xiong, M. Zhao, S. Hu, et al., Predictive value of left atrial strain analysis in adverse clinical events in patients with hypertrophic cardiomyopathy: a CMR study, BMC Cardiovasc. Disord. 23 (1) (2023) 42, https://doi.org/10.1186/s12872-023-03069-2.
[4] K. Leong, L. Howard, F. Lo Giudice, H. Pavey, R. Davies, G. Haji, et al., MRI feature tracking strain in pulmonary hypertension: utility of combined left atrial volumetric and deformation assessment in distinguishing post- from pre-capillary physiology, Front Cardiovasc. Med. 9 (2022) 787656, https://doi.org/10.3389/fcvm.2022.787656.
[5] J. Buggey, B.D. Hoit, Left atrial strain: measurement and clinical application, Curr. Opin. Cardiol. 33 (5) (2018) 479–485, https://doi.org/10.1097/HCO.0000000000000537.
[6] S.L. Gaynor, H.S. Maniar, S.M. Prasad, P. Steendijk, M.R. Moon, Reservoir and conduit function of right atrium: impact on right ventricular filling and cardiac output, Am. J. Physiol. Heart Circ. Physiol. 288 (5) (2005) H2140–H2145, https://doi.org/10.1152/ajpheart.00566.2004.
[7] R. Cau, P. Bassareo, J.S. Suri, G. Pontone, L. Saba, The emerging role of atrial strain assessed by cardiac MRI in different cardiovascular settings: an up-to-date review, Eur. Radiol. 32 (7) (2022) 4384–4394, https://doi.org/10.1007/s00330-022-08598-6.
[8] L. Thomas, T.H. Marwick, B.A. Popescu, E. Donal, L.P. Badano, Left atrial structure and function, and left ventricular diastolic dysfunction: JACC state-of-the-art review, J. Am. Coll. Cardiol. 73 (15) (2019) 1961–1977, https://doi.org/10.1016/j.jacc.2019.01.059.
[9] M.C. Halfmann, S. Altmann, U.J. Schoepf, C. Reichardt, J.B. Hennermann, K. F. Kreitner, et al., Left atrial strain correlates with severity of cardiac involvement in Anderson-Fabry disease, Eur. Radiol. 33 (3) (2023) 2039–2051, https://doi.org/10.1007/s00330-022-09183-7.
[10] P. Ponikowski, A.A. Voors, S.D. Anker, H. Bueno, J.G.F. Cleland, A.J.S. Coats, et al., 2016 ESC Guidelines for the diagnosis and treatment of acute and chronic heart failure: the task force for the diagnosis and treatment of acute and chronic heart failure of the European society of cardiology (ESC)Developed with the special contribution of the heart failure association (HFA) of the ESC, Eur. Heart J. 37 (27) (2016) 2129–2200, https://doi.org/10.1093/eurheartj/ehw128.
[11] J.L. Anderson, B.D. Horne, D.J. Pennell, Atrial dimensions in health and left ventricular disease using cardiovascular magnetic resonance, J. Cardiovasc. Magn. Reson. 7 (4) (2005) 671–675, https://doi.org/10.1081/jcmr-65617.
[12] E. Arbelo, A. Protonotarios, J.R. Gimeno, E. Arbustini, R. Barriales-Villa, C. Basso, et al., 2023 ESC Guidelines for the management of cardiomyopathies, Eur. Heart J. 44 (37) (2023) 3503–3626, https://doi.org/10.1093/eurheartj/ehad194.
[13] J. Schulz-Menger, D.A. Bluemke, J. Bremerich, S.D. Flamm, M.A. Fogel, M. G. Friedrich, et al., Standardized image interpretation and post-processing in cardiovascular magnetic resonance - 2020 update : society for cardiovascular magnetic resonance (SCMR): board of trustees task force on standardized post-processing, J. Cardiovasc. Magn. Reson. 22 (1) (2020) 19, https://doi.org/10.1186/s12968-020-00610-6.
[14] M.S. Nacif, A.D. Barranhas, E. Turkbey, E. Marchiori, N. Kawel, R.A. Mello, et al., Left atrial volume quantification using cardiac MRI in atrial fibrillation: comparison of the Simpson's method with biplane area-length, ellipse, and three-dimensional methods, Diagn. Interv. Radiol. 19 (3) (2013) 213–220, https://doi.org/10.5152/dir.2012.002.
[15] S. Leng, H. Ge, J. He, L. Kong, Y. Yang, F. Yan, et al., Long-term prognostic value of cardiac MRI left atrial strain in ST-segment elevation myocardial infarction, Radiology 296 (2) (2020) 299–309, https://doi.org/10.1148/radiol.2020200176.
[16] G.G. Blume, C.J. McLeod, M.E. Barnes, J.B. Seward, P.A. Pellikka, P.M. Bastiansen, et al., Left atrial function: physiology, assessment, and clinical implications, Eur. J. Echocardiogr. 12 (6) (2011) 421–430, https://doi.org/10.1093/ejechocard/jeq175.
[17] A.M. Maceira, J. Cosin-Sales, S.K. Prasad, D.J. Pennell, Characterization of left and right atrial function in healthy volunteers by cardiovascular magnetic resonance, J. Cardiovasc. Magn. Reson. 18 (1) (2016) 64, https://doi.org/10.1186/s12968-016-0284-8.
[18] F. Le Ven, K. Bibeau, E. De Larochelliere, H. Tizon-Marcos, S. Deneault-Bissonnette, P. Pibarot, et al., Cardiac morphology and function reference values derived from a large subset of healthy young Caucasian adults by magnetic resonance imaging, Eur. Heart J. Cardiovasc. Imaging. 17 (9) (2016) 981–990, https://doi.org/10.1093/ehjci/jev217.
[19] A.M. Maceira, J. Cosin-Sales, M. Roughton, S.K. Prasad, D.J. Pennell, Reference left atrial dimensions and volumes by steady state free precession cardiovascular magnetic resonance, J. Cardiovasc. Magn. Reson. 12 (1) (2010) 65, https://doi.org/10.1186/1532-429X-12-65.
[20] B.D. Hoit, Left atrial size and function: role in prognosis, J. Am. Coll. Cardiol. 63 (6) (2014) 493–505, https://doi.org/10.1016/j.jacc.2013.10.055.
[21] A.C. To, S.D. Flamm, T.H. Marwick, A.L. Klein, Clinical utility of multimodality LA imaging: assessment of size, function, and structure, JACC Cardiovasc. Imaging. 4 (7) (2011) 788–798, https://doi.org/10.1016/j.jcmg.2011.02.018.
[22] W.P. Abhayaratna, J.B. Seward, C.P. Appleton, P.S. Douglas, J.K. Oh, A.J. Tajik, et al., Left atrial size: physiologic determinants and clinical applications, J. Am. Coll. Cardiol. 47 (12) (2006) 2357–2363, https://doi.org/10.1016/j.jacc.2006.02.048.
[23] E. Donal, G.Y. Lip, M. Galderisi, A. Goette, D. Shah, M. Marwan, et al., EACVI/EHRA Expert consensus document on the role of multi-modality imaging for the evaluation of patients with atrial fibrillation, Eur. Heart J. Cardiovasc. Imaging. 17 (4) (2016) 355–383, https://doi.org/10.1093/ehjci/jev354.
[24] S. Altmann, M.C. Halfmann, I. Abidoye, B. Yacoub, M. Schmidt, P. Wenzel, et al., Compressed sensing acceleration of cardiac cine imaging allows reliable and reproducible assessment of volumetric and functional parameters of the left and right atrium, Eur. Radiol. 31 (10) (2021) 7219–7230, https://doi.org/10.1007/s00330-021-07830-z.
[25] J. Nguyen, J. Weber, B. Hsu, R.R. Mulyala, L. Wang, J.J. Cao, Comparing left atrial indices by CMR in association with left ventricular diastolic dysfunction and adverse clinical outcomes, Sci. Rep. 11 (1) (2021) 21331, https://doi.org/10.1038/s41598-021-00596-w.
[26] D.C. Peters, J. Lamy, A.J. Sinusas, L.A. Baldassarre, Left atrial evaluation by cardiovascular magnetic resonance: sensitive and unique biomarkers, Eur. Heart J. Cardiovasc. Imaging. 23 (1) (2021) 14–30, https://doi.org/10.1093/ehjci/jeab221.
[27] E. Akintoye, M. Majid, A.L. Klein, M. Hanna, Prognostic Utility of Left Atrial Strain to Predict Thrombotic Events and Mortality in Amyloid Cardiomyopathy, JACC Cardiovasc Imaging. 16 (11) (2023) 1371–1383, https://doi.org/10.1016/j.jcmg.2023.01.015.
[28] J.A. Chirinos, M. Sardana, B. Ansari, V. Satija, D. Kuriakose, I. Edelstein, et al., Left Atrial phasic function by cardiac magnetic resonance feature tracking is a strong predictor of incident cardiovascular events, Circ. Cardiovasc. Imaging. 11 (12) (2018) e007512, https://doi.org/10.1161/CIRCIMAGING.117.007512.
[29] A. Sonaglioni, M.D. Cara, G.L. Nicolosi, A. Eusebio, M. Bordonali, P. Santalucia, et al., Rapid risk stratification of acute ischemic stroke patients in the emergency department: the incremental prognostic role of left atrial reservoir strain, J. Stroke Cerebrovasc. Dis. 30 (11) (2021) 106100, https://doi.org/10.1016/j.jstrokecerebrovasdis.2021.106100.
[30] E.S.J. Tan, X. Jin, Y.Y. Oon, S.P. Chan, L. Gong, J.B. Lunaria, et al., Prognostic value of left atrial strain in aortic stenosis: A competing risk analysis, J. Am. Soc. Echocardiogr. 36 (1) (2023) 29–37 e5, https://doi.org/10.1016/j.echo.2022.10.011.
[31] J. Nadjiri, A.L. Zaschka, A.S. Straeter, A. Sauter, M. Englmaier, F. Weis, et al., Evaluation of a shortened cardiac MRI protocol for left ventricular examinations: diagnostic performance of T1-mapping and myocardial function analysis, BMC Med. Imaging 19 (1) (2019) 57, https://doi.org/10.1186/s12880-019-0358-9.
[32] L. Li, X. Chen, G. Yin, W. Yan, C. Cui, H. Cheng, et al., Early detection of left atrial dysfunction assessed by CMR feature tracking in hypertensive patients, Eur. Radiol. 30 (2) (2020) 702–711, https://doi.org/10.1007/s00330-019-06397-0.
[33] J. Wen, X. Zhang, S. Li, X. Tao, Q. Fang, S. Zhou, et al., Identification of heart failure with preserved ejection fraction in patients with hypertension: a left atrial myocardial strain cardiac magnetic resonance study, Quant. Imaging Med. Surg. 13 (5) (2023) 2881–2894. https://doi.org/10.21037/qims-22-1012.
[34] Y. Yang, G. Yin, Y. Jiang, L. Song, S. Zhao, M. Lu, Quantification of left atrial function in patients with non-obstructive hypertrophic cardiomyopathy by cardiovascular magnetic resonance feature tracking imaging: a feasibility and reproducibility study, J. Cardiovasc. Magn. Reson. 22 (1) (2020) 1, https://doi.org/10.1186/s12968-019-0589-5.
[35] H. Li, H. Wang, T. Wang, C. Jin, M. Lu, B. Liu, Different phenotype of left atrial function impairment in patients with hypertrophic cardiomyopathy and hypertension: comparison of healthy controls, Front Cardiovasc. Med. 10 (2023) 1027665, https://doi.org/10.3389/fcvm.2023.1027665.
[36] V. Mor-Avi, R.M. Lang, L.P. Badano, M. Belohlavek, N.M. Cardim, G. Derumeaux, et al., Current and evolving echocardiographic techniques for the quantitative evaluation of cardiac mechanics: ASE/EAE consensus statement on methodology and indications endorsed by the Japanese society of echocardiography, J. Am. Soc. Echocardiogr. 24 (3) (2011) 277–313, https://doi.org/10.1016/j.echo.2011.01.015.
[37] A. Dick, B. Schmidt, G. Michels, A.C. Bunck, D. Maintz, B. Baessler, Left and right atrial feature tracking in acute myocarditis: A feasibility study, Eur. J. Radiol. 89 (2017) 72–80, https://doi.org/10.1016/j.ejrad.2017.01.028.
[38] J. Lee, K.S. Choo, Y.J. Jeong, G. Lee, M. Hwang, M.R. Abraham, et al., Left atrial strain derived from cardiac magnetic resonance imaging can predict outcomes of patients with acute myocarditis, Korean J. Radiol. 24 (6) (2023) 512–521, https://doi.org/10.3348/kjr.2022.0898.
[39] K. Fujimoto, K. Inoue, M. Saito, H. Higashi, T. Kono, T. Uetani, et al., Incremental value of left atrial active function measured by speckle tracking echocardiography in patients with hypertrophic cardiomyopathy, Echocardiography 35 (8) (2018) 1138–1148, https://doi.org/10.1111/echo.13886.
[40] V.T. Truong, C. Palmer, S. Wolking, B. Sheets, M. Young, T.N.M. Ngo, et al., Normal left atrial strain and strain rate using cardiac magnetic resonance feature tracking in healthy volunteers, Eur. Heart J. Cardiovasc. Imaging. 21 (4) (2020) 446–453, https://doi.org/10.1093/ehjci/jez157.