Experimental Study on Evaluation of Left Atrial and Ventricular Function in Hypertensive Heart Disease by Cardiac Magnetic Resonance

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Abstract: Objective: To investigate the value of cardiac magnetic resonance feature tracking (CMR-FT) in assessing left heart function in hypertensive heart disease (HHD) patients and to preliminarily explore the relationship between left atrial (LA) and left ventricular (LV) function1. Methods: Ten Bama minipigs were randomly divided into an experimental group (N=6) and a control group (N=4). The experimental group underwent laparotomy with left renal artery ligation to establish a hypertension model, whereas the control group underwent laparotomy without ligation. CMR-FTs were performed at baseline and at 16 weeks post-surgery. Global LA and LV functional parameters were measured via CVI42 postprocessing software. Results: Left atrial volumetric indices LAVImin and LAVImax were significantly greater in the hypertension group at 16 weeks (LAVImin 17.65±1.66 vs 11.13±1.60 mL/m², P<0.001; LAVImax 27.05±2.19 vs 20.75±3.13 mL/m², P=0.005). LA reservoir and conduit function deteriorated early: εs and εe were decreased at 16 weeks (εs 27.22±3.71 vs 39.53±2.72, P<0.001; εe 12.10±2.02 vs 23.00±1.77, P<0.001). LV volumetric parameters and LVEF remained comparable between groups at all time points (all P>0.05), whereas LV strain indices were significantly impaired in the hypertension group at 16 weeks (e.g., LVRS 29.55±1.80 vs 43.18±1.35; LVCS −16.58±0.87 vs −19.63±0.99; LVLS −12.63±1.73 vs −18.33±0.76; all P≤0.039). Moreover, the LVLS was positively correlated with εs (r=0.814) and εe (r=0.875) and negatively correlated with LA volume (LAVmin r=−0.817; LAVmax r=−0.907), whereas the LVRS was also associated with LA function (all P<0.05). Conclusion: CMR-FT can detect structural and functional impairments of the LA and LV in early-stage HHD earlier, more sensitively, and more accurately than conventional cardiac functional parameters. Furthermore, significant correlations exist between LA and LV functional parameters.

***Keywords*:** hypertensive heart disease; cardiac magnetic resonance; myocardial strain; left ventricular function; left atrial function

1. Introduction

Hypertension is a primary risk factor for cardiovascular, cerebrovascular, and renal diseases. Globally, it imposes staggering clinical and socioeconomic burdens, affecting approximately one billion individuals and precipitating millions of deaths annually[1]. In the heart, chronically elevated blood pressure induces hypertensive heart disease (HHD), which is characterized by progressive structural and functional deterioration of the myocardium. The hallmark phenotypes of HHD include left ventricular hypertrophy (LVH) and subsequent systolic and diastolic dysfunction[2]. The pathophysiology of LVH involves a complex interplay of mechanical stress, neurohormonal activation, growth factors, and cytokine-mediated signaling. Physiologically, the left atrium (LA) plays a pivotal role in cardiac hemodynamics: it functions as a reservoir to collect pulmonary venous flow during left ventricular (LV) systole and acts as a conduit to transport blood to the LV during diastole. In the setting of hypertension, increased LV afterload necessitates increased generation of LV pressure, which retrogradely elevates LV filling pressures and, consequently, LA wall stress[3]. Hypertension-mediated LA structural and functional remodeling is increasingly recognized as a fundamental substrate or precipitating factor for the development of heart failure[4]. Therefore, characterizing the process of LA remodeling in hypertension is critical. Notably, emerging evidence suggests that LA functional abnormalities may manifest prior to overt LV structural remodeling[5]. However, the precise relationship between this aberrant LA function and subclinical LV dysfunction remains insufficiently evaluated.

Although echocardiography is widely utilized for cardiac assessment, it is inherently limited by operator dependence and low reproducibility. Cardiac magnetic resonance (CMR) offers a comprehensive evaluation of cardiac morphology, function, and tissue characterization. A significant diagnostic challenge in HHD is that conventional global functional parameters often remain preserved or even elevated during the compensated phase, rendering them insensitive markers for early myocardial injury[6]. In contrast, CMR feature tracking (CMR-FT) has emerged as a robust technique capable of quantifying subclinical myocardial dysfunction through myocardial strain parameters.

Animal models are indispensable for elucidating the pathogenesis of hypertension and its associated cardiac

remodeling[7]. Porcine models, in particular, are highly homologous to humans in terms of cardiovascular physiology, anatomy, and function[8]. In this study, we established a porcine model of HHD via left renal artery ligation to longitudinally assess left heart mechanics. By leveraging CMR-FT, we aimed to quantitatively evaluate subclinical left heart dysfunction and preliminarily investigate the dynamic coupling between the LA and LV function. This study aimed to establish a reliable noninvasive imaging strategy for the early diagnosis of HHD, provide a theoretical basis for further mechanistic studies on atrioventricular coupling, and offer reference data regarding the temporal progression of HHD in a clinical context.

2. Materials and methods

This study was approved by the Hospital Animal Ethics Committee (No. YXKT2024L016). Ten Bama minipigs (aged 9–12 months; weighing 25–30 kg) were included and randomized into a hypertension group (N=6) and a control group (N=4).

2.1 Animal Model Establishment

All surgical procedures were performed under general anesthesia. The animals were restrained, and venous access was established via the marginal ear vein. Anesthesia was induced and maintained with Propofol (AstraZeneca UK Limited) administered as a bolus (5–8 mL/dose). Preoperative ceftiofur hydrochloride (5 mg/kg) was administered for infection prophylaxis. In the hypertension group, the abdomen was prepared and draped. A laparotomy was performed through a left paramedian incision (along the lateral edge of the rectus abdominis) to expose the retroperitoneum. The left renal artery was isolated and ligated using No. 1 suture material. The control group underwent an identical surgical procedure with renal artery isolation but without ligation. Postmodel analgesia was provided by intramuscular injection of ketoprofen (3 mg/kg) once daily for three consecutive days.

2.2 Acquisition of left heart functional parameters

CMR image acquisition Cardiac magnetic resonance (CMR) examinations were performed at baseline, 4 weeks, and 16 weeks post-operation via a 3.0-T scanner (MAGNETOM Skyra, Siemens Healthineers). Balanced steady-state free precession (bSSFP) cine sequences were acquired in the left ventricular (LV) two-chamber, four-chamber, and short-axis planes (covering the entire ventricle from the base to the apex). The imaging parameters were as follows: slice thickness, 6 mm; TR, 38.52 ms; TE, 1.40 ms; FOV, 270 × 270 mm; and flip angle, 49°.

Image postprocessing Image analysis was performed via CVI42 (Circle Cardiovascular Imaging, Inc., Calgary, Canada). Left Atrial (LA) Volumetry: Using the biplane long-axis (LAX) module, LA endocardial contours were manually traced on cine images at LV end-systole (LAVmax) and LV end-diastole (LAVmin). Volumes were indexed to body surface area (BSA) to derive the LA maximum volume index (LAVImax) and minimum volume index (LAVImin). Left Ventricular (LV) Function: Using the 3D short-axis (SAX) module, endocardial and epicardial contours (excluding papillary muscles and epicardial fat) were semiautomatically traced on the short-axis stack and manually corrected. LV functional parameters, including the end-diastolic volume (LVEDV), end-systolic volume (LVESV), stroke volume (SV), and ejection fraction (LVEF), were calculated. Volumetric indices (LVEDVI, LVESVI, and LVSVI) were derived on the basis of the BSA. Feature Tracking (CMR-FT) LA Strain: LA endocardial contours (excluding pulmonary veins and the left atrial appendage) were tracked in the LV systolic and diastolic phases via the strain analysis module. The software automatically calculates global LA longitudinal strain parameters: total strain (εs), active strain (εa), and passive strain εe = (εs -εa).LV strain: LV radial strain (LVRS), circumferential strain (LVCS), and longitudinal strain (LVLS) were derived via tissue feature tracking technology.

2.3 Statistical analysis

Continuous variables were tested for normality via the Kolmogorov–Smirnov test. The data are presented as the means ± standard deviations (SDs) or medians (interquartile ranges). Intergroup comparisons: Differences between the hypertension and control groups at each time point were assessed via the independent samples t test or Mann–Whitney U test. Correlations: The relationships between LA and LV functional parameters were evaluated via Pearson correlation analysis. All the statistical analyses were performed via SPSS version 27.0 (IBM Corp, Armonk, NY, USA). Statistical significance was defined as $P < 0.05$.

3. Results

All the animals successfully completed the experimental protocol. A total of 10 Bama minipigs were included in the final analysis, consisting of 6 in the hypertension group and 4 in the control group. CMR-FT image acquisition and postprocessing analysis were completed for all animals at baseline and 16 weeks post-surgery.

3.1 Analysis of the functional parameters of the left atrium

Longitudinal analysis revealed progressive LA remodeling in the hypertension group. Both LAVmin and LAVmax increased continuously from baseline to 16 weeks in both groups. the hypertension group presented significantly greater LAVmin, LAVmax, LAVImin, and LAVImax values than did the control group at 16 weeks ($P < 0.05$). LA strain parameters demonstrated a progressive decline in the hypertension group. εa,εs and εe were significantly lower in the hypertension group than in the control group at 16 weeks ($P < 0.05$) (Table 1.)

Table 1. Comparison of left atrial function parameters at baseline and 16 weeks after model induction between the hypertension group and the experimental group

	Baseline		t	P	16 weeks		t	P
	HHD	Control			HHD	Control		
LAVmin	9.62±1.45	9.95±1.30	-0.369	0.722	22.23±1.69*	17.20±2.93*	3.482	0.008
LAVmax	15.65±2.25	15.43±2.85	0.140	0.892	34.03±1.98*	25.08±3.45*	5.276	0.001
LAVImin	11.52±1.62	12.40±1.49	-0.869	0.410	17.65±1.66*	11.13±1.60	6.174	0.000
LAVImax	18.70±2.37	19.25±3.58	-0.296	0.775	27.05±2.19*	20.75±3.13	3.779	0.005
εs	44.22±2.81	42.85±3.27	0.708	0.499	27.22±3.71*	39.53±2.72	-5.659	0.000
εa	19.88±1.33	19.43±0.86	0.604	0.563	15.20±1.65*	17.88±1.75	-2.456	0.040
εe	24.33±1.59	23.93±2.29	0.336	0.746	12.10±2.02*	23.00±1.77	-8.760	0.000

Note: * indicates a difference within the same group compared with the baseline ($P<0.05$).

3.2 Left Ventricular Functional Parameter Analysis

Systolic and diastolic blood pressures in the hypertension group increased progressively, with significant increases compared with those in the control group at 16 weeks ($P < 0.05$). Although the LVEDV, LVESV, and SV increased over time within the groups (reflecting physiological growth), there were no statistically significant differences in the LVEDV, LVESV, SV, or LVEF between the hypertension and control groups at any time point ($P > 0.05$). These findings indicate preserved global systolic function and volume in the early stages of HHD. In contrast to the volumetric parameters, the LV deformation markers deteriorated early. LVRS, LVCS, and LVLS in the hypertension group decreased progressively from baseline. Compared with those of the controls, significant reductions in these strain parameters at 16 weeks ($P < 0.05$). (Table 2)

Table 2. Comparison of left ventricular function parameters at baseline and 16 weeks after model induction between the hypertension group and the control group at each time point

	Baseline		t	P	16 weeks		t	P
	HHD	Control			HHD	Control		
SBP	108.17±4.02	109.25±10.69	-0.231	0.823	144.33±3.72*	109.75±6.45	10.877	0.000
DBP	67.33±3.33	71.50±7.23	-1.253	0.246	96.67±3.01*	71.75±6.4	8.421	0.000
LVEDV	45.00±3.50	43.95±3.99	0.441	0.671	63.93±3.33*	64.38±4.02*	-0.190	0.854
LVESV	13.07±3.77	13.70±3.01	-0.280	0.787	20.18±3.38*	21.43±3.17*	-0.582	0.577
LVSV	32.02±3.93	30.25±1.31	0.853	0.418	43.75±4.43*	42.95±4.64*	0.275	0.790
LVEF	70.20±7.67	69.10±4.16	0.495	0.634	67.88±5.76	66.73±5.19	0.323	0.755
LVEDVI	53.88±3.57	54.75±3.99	-0.360	0.728	52.90±2.96	53.08±2.50	-0.097	0.925
LVESVI	15.63±4.45	17.05±3.43	-0.535	0.607	16.65±2.83	17.68±2.52	-0.585	0.575
LVSVI	38.38±4.49	37.68±1.00	0.305	0.768	37.20±2.40	35.43±3.57	0.950	0.370
LVRS	42.58±2.24	44.48±3.71	-1.018	0.338	29.55±1.80*	43.18±1.35	-12.857	0.000
LVCS	-20.78±1.66	-21.13±1.81	0.308	0.766	-16.58±0.87*	-19.63±0.99	5.151	0.001
LVLS	-18.27±1.28	-18.60±1.08	0.428	0.680	-12.63±1.73*	-18.33±0.76	6.092	0.000

Note: * indicates a difference within the same group compared with the baseline ($P<0.05$)

3.3 Correlation analysis of left ventricular and left atrial parameters

Significant coupling between LV mechanics and LA function: LVLS was significantly positively correlated with εs ($r=0.814$; εe: $r=0.875$, both $P < 0.05$) and significantly negatively correlated with LA volume (LAVmin: $r=-0.817$; LAVmax: $r=-0.907$; both $P < 0.05$). LVRS was positively correlated with εe ($r=0.855$, $P < 0.05$) and negatively correlated with LA volume (LAVmin: $r=-0.812$; LAVmax: $r=-0.860$; both $P < 0.05$). (Figure 1).

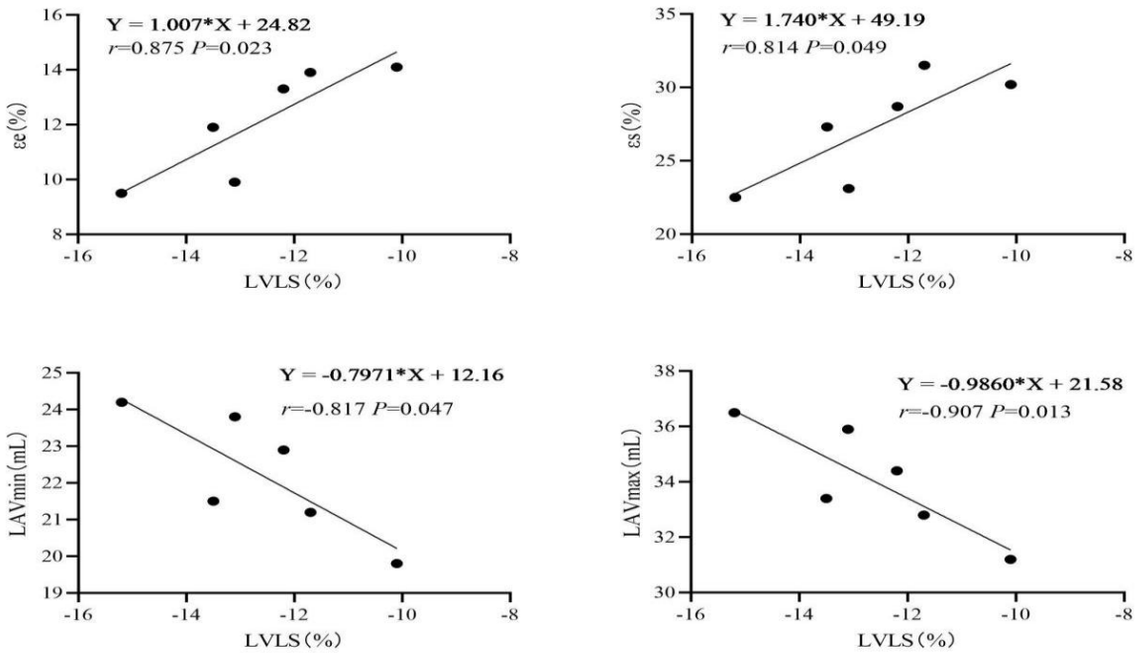

Figure 1. Correlation between left ventricular longitudinal strain (LVLS) and left atrial volume and strain.

4. Discussion

Clinically, the left ventricular ejection fraction (LVEF) remains the standard metric for assessing systolic function. However, the LVEF is inherently limited, as it reflects only global volumetric changes, failing to capture intrinsic myocardial contractile properties or regional deformation abnormalities[9]. Myocardial strain, defined as the fractional change in myocardial length throughout the cardiac cycle, offers a superior measure of deformation capability that is independent of global cardiac translation and tethering effects[10].

In this study, we conducted a comprehensive comparative analysis of conventional functional parameters and myocardial strain characteristics in HHD patients. Notably, conventional indices (LVEF, LVEDV, LVESV, LVSV, and their indexed values) remained comparable between the hypertension and control groups at matched time points. These findings suggest that overt volumetric remodeling is absent during the early stages of HHD. Conversely, myocardial strain parameters exhibited significantly greater sensitivity in detecting subclinical dysfunction. Our data revealed significant differences in the LVLS, LVRS, and LVCS between the groups at 16 weeks post-surgery. Mechanistically, these early functional impairments likely stem from pathological processes such as microvascular rarefaction and dysregulated calcium handling, which precede overt cardiomyocyte hypertrophy and interstitial fibrosis, ultimately compromising myocardial deformation capability [11]. These findings are concordant with those of Li et al. [12], who reported reduced multidirectional strain (LVLS, LVRS, and LVCS) in HHD patients despite preserved conventional functional parameters, indicating that hypertensive remodeling is a global phenomenon affecting the myocardium diffusely rather than segmentally.

Previous studies by Fung et al. [13] and Chen et al.[14] observed reduced strain parameters despite preserved LA volumes in hypertensive cohorts. However, our longitudinal assessment revealed that by 16 weeks, significant LA dilation (increased LAVmax and LAVmin) and a decline in εa became evident. Our results align with those of Li et al.[15], who noted that εa remains preserved in hypertensive patients without LVH but decreases in those with LVH. We hypothesize that in the nascent stages of HHD, a compensatory mechanism augments LA contractile function εa to maintain adequate LV filling pressures and cardiac output against early diastolic dysfunction. As the disease progresses, worsening LV fibrosis and diastolic stiffness eventually overwhelm this compensation, leading to a significant decrease in LA compliance and a subsequent decline in contractile function [16].

Atrioventricular Coupling: LA–LV interaction analysis of atrioventricular coupling revealed a robust correlation between LA and LV mechanics. Specifically, LVLS was positively correlated with εs and εe, whereas both LVRS and LVLS were negatively correlated with LA volume (LAVmin, LAVmax). Additionally, the LVRS was positively correlated with εe. These associations are consistent with findings of Fung et al. [17].

5. Conclusion

In conclusion, myocardial strain parameters derived from CMR-FT allow for the assessment of structural and functional impairments of the left heart in early-stage HHD earlier, more sensitively, and more accurately than conventional cardiac functional parameters. Additionally, significant correlations exist between left atrial and left ventricular functional parameters. The advancement and application of myocardial strain analysis hold substantial value for further exploration of the intrinsic link between myocardial mechanics and function. Furthermore, the detection of myocardial strain abnormalities is of significant clinical importance for the subclinical diagnosis and evaluation of HHD, potentially guiding clinicians in formulating personalized therapeutic strategies for patients in the subclinical phase.

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Declaration

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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