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Evaluation of elevated left ventricular end diastolic pressure in patients with preserved ejection fraction using cardiac magnetic resonance

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Abstract

Objectives This study aims to validate the reliability of cardiac magnetic resonance (CMR) parameters for estimating left ventricular end diastolic pressure (LVEDP) in heart failure patients with preserved ejection fraction (HFpEF) and compare their accuracy to conventional echocardiographic ones, with reference to left heart catheterisation.

Methods Sixty patients with exertional dyspnoea (New York Heart Association function class II to III) were consecutively enrolled. CMR-derived time-volume curve and deformation parameters, conventional echocardiographic diastolic indices as well as LVEDP evaluated by left heart catheterisation were collected and analysed.

Results Fifty-one patients, who accomplished all three examinations, were divided into HFpEF group and non-HFpEF group based on LVEDP measurements. Compared to the non-HFpEF group, CMR-derived time-volume curve showed lower peak filling rate adjusted for end diastolic volume (PFR/EDV, $p = 0.027$), longer time to peak filling rate (T-PFR, $p < 0.001$), and increased T-PFR in one cardiac cycle (%T-PFR, $p < 0.001$) in HFpEF group. In multivariable linear regression analysis, %T-PFR ($\beta = 0.372$, $p = 0.024$), left ventricular global peak longitudinal diastolic strain rate (LDSR, $\beta = -0.471$, $p = 0.006$), and E/e' ($\beta = 0.547$, $p = 0.001$) were independently associated with invasively measured LVEDP. The sensitivity and specificity of E/e' and LDSR for predicting the elevated LVEDP were 76%, 92% and 76%, 89%, respectively.

Conclusions These findings suggest that CMR-derived time-volume curve and strain indices could predict HFpEF patients. Not only E/e' assessed by echocardiography but also the CMR-derived %T-PFR and LDSR correlated well with LVEDP. These non-invasive parameters were validated to evaluate the left ventricular diastolic function.

Key Points

- *The abnormal time-volume curve revealed insufficient early diastole in HFpEF patients.*
- *Non-invasive parameters including E/e', %T-PFR, and LDSR correlated well with LVEDP.*

Keywords Heart failure, diastolic · Ventricular function, left · Ventricular pressure · Magnetic resonance imaging

Abbreviations

%T-PFR	Time to peak filling rate in one cardiac cycle
ASE	American Society of Echocardiography
BMI	Body mass index
BNP	Brain natriuretic peptide
BSA	Body surface area
CDSR	Left ventricular global peak circumferential diastolic strain rate
CMR	Cardiac magnetic resonance
EDV	End diastolic volume

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EGFR	Estimated glomerular filtration rate
HF	Heart failure
HFpEF	Heart failure with preserved ejection fraction
HFrEF	Heart failure with reduced ejection fraction
ICC	Intraclass correlation coefficient
LAVI	BSA-indexed left atrial volume
LDSR	Left ventricular global peak longitudinal diastolic strain rate
LV	Left ventricular
LVEDP	Left ventricular end diastolic pressure
LVEDVI	BSA-indexed LV end diastolic volume
LVEF	Left ventricular ejection fraction
LVESVI	BSA-indexed LV end-systolic volume
LVMI	BSA-indexed LV mass
PFR	Peak filling rate
PFR/EDV	Peak filling rate adjusted for end diastolic volume
PFV	Peak filling volume
RDSR	Left ventricular global peak radial diastolic strain rate
T-PFR	Time to peak filling rate
TDI	Tissue Doppler imaging

Introduction

Heart failure with preserved ejection fraction (HFpEF) is characterised by signs or symptoms of heart failure (HF) and has preserved ejection fraction and evidence of structural or functional cardiac abnormalities. Its overall incidence accounts for more than half of the total burden of HF [1–3]. Of note, HFpEF has similar morbidity as HF with reduced ejection fraction (HFrEF), but has reduced detection rate due to more challenging and complicated diagnostic criteria. Elevated left ventricular (LV) filling pressure remains to be the diagnostic hallmark of HFpEF by LV catheterisation or echocardiography. Estimating intracardiac pressure with left heart catheterisation is the 'gold standard' to confirm LV compliance, but it is less applied due to its invasiveness. Echocardiography, as a portable modality, is widely used in clinics for diagnosing HFpEF. However, according to the most recent guidelines of the American Society of Echocardiography (ASE), 2-dimensional, conventional and tissue Doppler variables should be determined collectively when the diagnosis of HFpEF is being considered [4].

Cardiac magnetic resonance (CMR) is a high spatial and temporal resolution tool that allows for the precise measurement of LV volume without geometric assumptions [5]. Cine short-axis views by CMR make it more accurate than echocardiography in assessing LV morphology [6]. Most of the CMR studies have mainly focused on the evaluation of cardiac systolic function. In addition, precise time-volume curve [7, 8] and strain analysis [9] allow quantification of LV global as well as regional diastolic function. Few studies have compared CMR findings with invasively measured intracardiac pressures. Therefore, the aim of this study was to validate CMR parameters for the estimation of left ventricular end diastolic pressure (LVEDP) to identify HFpEF patients and compare their accuracy with echocardiographic findings.

Methods

Study population

Sixty patients with exertional dyspnoea (New York Heart Association function class II to III) were prospectively enrolled in this study from July 1, 2016, to June 1, 2017. Echocardiography, CMR, and left heart catheterisation were accomplished in all subjects within 2 weeks of enrolment. All patients had preserved LV ejection fraction (LVEF) and normal LV size as assessed by echocardiography and CMR (LVEF $\geq$ 50%, indexed LV end diastolic volume $\leq$ 97 mL/m^2). Based on the LVEDP recorded by left heart catheterisation, subjects were divided dichotomously into two groups: patients with LVEDP > 16 mmHg were defined as HFpEF group, and the remaining patients (0 < LVEDP $\leq$ 16 mmHg) as non-HFpEF group [10]. Exclusion criteria were as follows: (1) non-sinus rhythm, (2) estimated glomerular filtration rate (EGFR) < 30 mL/min/1.73m^2, (3) history of myocardial infarction, or an evidence of a significant coronary artery stenosis $\geq$ 50% (in proximal or medium segment of the main coronary arteries by quantitative coronary angiography), (4) moderate to severe valvular stenosis or regurgitation judged by echocardiography, (5) any suspected or confirmed cardiomyopathies (such as dilated cardiomyopathy, hypertrophic cardiomyopathy, restrictive cardiomyopathy), and (6) instances of any contraindications which caused patients to fail to accomplish CMR or left heart catheterisation test. Of the 60 patients who were eligible to enrol in this study, 5 patients failed to accomplish left heart catheterisation or CMR test, and 4 patients were diagnosed with coronary artery disease. All data from the remaining 51 patients were analysed in this study. Investigations were approved by the Institutional Ethics Committee of Shanghai Jiao Tong University Affiliated Sixth People's Hospital and all participants were enrolled by qualified cardiologists who were trained for the inclusion and exclusion criteria of the study. Informed consents were obtained from all participants.

Echocardiography

Echocardiographic imaging was performed using an iE33 echocardiographic scanner (Philips Medical Systems) equipped with a S5-1 probe. Acquisitions from at least three consecutive heartbeats were stored in raw data format for offline analysis. LVEF

was measured using the modified Simpson biplane method from apical imaging planes. Early and late diastolic mitral valve inflows (E- and A-waves) were recorded by pulsed wave Doppler at the mitral valve leaflet tips in an apical four-chamber view. Pulsed wave tissue Doppler imaging (TDI) was applied to record early diastolic tissue velocity (e') at the septal and lateral positions. The E/e' ratio was calculated using e' as the average value of septal and lateral e'.

CMR parameters acquisition

CMR was performed using a 3.0-Tesla scanner (Achieva 3.0 T, Philips Medical Systems). Images were assessed using retrospective ECG-gated, segmented steady state short-axis cine images (from mitral annulus to LV apex). All images were acquired at end-expiration using the following parameters: repetition time 3.2 ms, echo time 1.5 ms, flip angle 45°, slice thickness 8 mm, no inter-slice gap, matrix 232 × 219 [11]. LV functions (LVEF, LV volumes, and LV mass) were measured by tracing the epicardial and endocardial borders of the short-axis cine images at end diastole and end systole automatically by using commercial software (cvi42; Circle Cardiovascular Imaging) and manually adjusted. Meanwhile, the time-volume curve was generated by continuously tracing endocardial borders in at least two complete cardiac cycles automatically and adjusted manually. LV peak filling rate (PFR) was obtained from LV time-volume curve and was defined as maximal change in the LV volume during sequential temporal phases (Δ volume/Δ phase). This index was adjusted for LV end diastolic volume (LVEDV) to generate standardised peak filling rate (PFR/EDV). Time to peak filling rate (T-PFR) was defined as the time interval between the beginning of the systole and LV peak filling rate point and can be recognised automatically. The T-PFR in one cardiac cycle (%T-PFR) was obtained by T-PFR divided by the time interval of one cardiac cycle. The peak filling volume (PFV) was the filling volume at peak filling rate.

Myocardial deformation was evaluated by tissue tracking based on CMR cine images. To assess LV diastolic function, the parameters of LV global peak longitudinal diastolic strain rate (LDSR), circumferential diastolic strain rate (CDSR) and radial diastolic strain rate (RDSR) should be generated.

Left heart catheterisation

In each patient, a fluid-filled 6F pigtail catheter was balanced and placed into the middle of the left ventricle percutaneously from the radial artery. LV pressure was obtained in more than three complete cardiac cycles and outflow tract pressure was recorded continuously when the catheter was pulled back across the aortic valve. Moderate to severe aortic stenosis was excluded, if a systolic pressure gradient was detected. LV pressure was digitally recorded using a commercial haemodynamic recording system (AXIOM Sensis, Siemens). The measurement of LVEDP was adjusted by hand at the start point of QRS wave on an electrocardiograph, which was just before the onset of rapid rise in LV systolic pressure.

Data reproducibility

All subjects were evaluated for inter- and intra-observer variability of the measurements. All LV filling patterns and deformation parameters were blindly analysed by two independent observers (JYZ and YJT). Data from separate observers were used to test the interobserver variability. Both observers re-analysed their own recordings within 2 weeks to test the intra-observer variability.

Statistical analysis

Summary statistics of clinical and imaging data were expressed as means ± SD or percentage, as appropriate. Comparisons between the groups were performed using the *t* test. A chi-square test was performed to calculate the categorical variables. The relationship between invasive and non-invasive parameters was assessed using linear regression. A multivariable linear regression analysis was performed to identify independent contributors of invasive LVEDP. Receiver operating characteristic curve analysis was used to identify parameters that were best to predict LVEDP > 16 mmHg. The intraclass correlation coefficient (ICC) was used to determine inter- and intra-observer reproducibility. $p < 0.05$ was considered to be statistically significant. All calculations were performed using the standard statistical software IBM SPSS 22.0.

Results

Study demographics

A total of 51 patients (45% men), with mean age of 67 ± 9 years undergoing echocardiography, CMR, and left heart catheterisation were analysed. Twenty-five patients (69 ± 8 years; 53% men) with elevated LVEDP (LVEDP > 16 mmHg) were classified into HFpEF group. The remaining 26 patients (65 ± 10 years; 38% men) with normal LVEDP (0 < LVEDP ≤ 16 mmHg) were classified into the non-HFpEF group. There were no significant differences between the two groups with respect to body mass index (BMI), body surface area (BSA), heart rate, blood pressure, and comorbidities. The characteristics of the study population are presented in Table 1.

Table 1 Baseline demographics and clinical variables of the study population

Variables	Non-HFpEF ($n = 26$)	HFpEF ($n = 25$)	p value
LVEDP (mmHg)	9 ± 4	19 ± 2*	< 0.001
Age (years)	65 ± 10	69 ± 8	0.119
Gender (male), %	10 (38%)	13 (53%)	0.331
BMI (kg/m^2)	24.7 ± 2.0	25.9 ± 2.7	0.083
BSA (m^2)	1.71 ± 0.14	1.74 ± 0.13	0.376
Heart rate (beat/min)	73 ± 10	72 ± 9	0.901
Systolic blood pressure (mmHg)	130 ± 17	134 ± 14	0.297
Diastolic blood pressure (mmHg)	77 ± 12	75 ± 10	0.747
Comorbidities			
HTN (%)	13 (50%)	17 (67%)	0.192
DM (%)	12 (47%)	15 (60%)	0.322

HFpEF heart failure with preserved ejection fraction, *LVEDP* left ventricular end diastolic pressure, *BMI* body mass index, *BSA* body surface area, *HTN* hypertension, *DM* diabetes mellitus

*$p < 0.05$

Diastolic inflow evaluated by echocardiography and CMR

In spite of the similar values for E, A, and E/A between the HFpEF and non-HFpEF groups, a lower mean e' value (5.8 ± 0.9 vs. 7.4 ± 1.0 cm/s, $p < 0.001$) resulted in a higher E/e' ratio in the HFpEF group compared to the non-HFpEF group (12.7 ± 3.1 vs. 9.4 ± 1.4, $p < 0.001$). Besides, CMR-derived LV time-volume curve showed lower PFR/EDV, longer T-PFR, and increased %T-PFR in HFpEF group when compared with non-HFpEF group (2.1 ± 0.8 vs. 2.6 ± 0.8 s^{-1}, $p = 0.027$ and 504 ± 41 vs. 423 ± 83 ms, $p < 0.001$, 50.6 ± 8.7 vs. 60.8 ± 8.4%, $p < 0.001$). No differences were observed in the PFR and PFV between the two groups. The echocardiographic and CMR diastolic inflow parameters are presented in Fig. 1 and Table 2. Two typical cases with LV time-volume curve from HFpEF group and non-HFpEF group are shown in Fig. 2, respectively.

CMR measurements of left heart functions and strains

BSA-indexed left atrial volume (LAVI) was significantly increased in HFpEF group (45.7 ± 11.8 vs. 35.6 ± 11.7 mL/m^2, $p = 0.004$). Besides, no differences were observed in BSA-indexed LV end diastolic volume (LVEDVI), LV end-systolic volume (LVESVI), and LV mass (LVMI) between the two groups. In addition, LV global peak diastolic strain rate including LDSR (0.61 ± 0.15 vs. 0.93 ± 0.23 s^{-1}, $p < 0.001$), CDSR (0.90 ± 0.24 vs. 1.07 ± 0.24 s^{-1}, $p = 0.016$), and RDSR (− 2.63 ± 1.05 vs. − 3.37 ± 1.14 s^{-1}, $p = 0.021$) were significantly lower in the HFpEF group. An overview of CMR measurements of LV functions and strains is detailed in Table 2.

Echocardiographic and CMR predictors of LVEDP

Based on univariable linear regression analysis, a significantly positive correlation was observed between LVEDP and echocardiography that assessed E/e' ($r = 0.504$, $p < 0.001$). There were also significantly positive correlations between LVEDP and CMR predictors including T-PFR ($r = 0.285$, $p = 0.043$), %T-PFR ($r = 0.381$, $p = 0.006$) and inverse correlation between LVEDP and LDSR ($r = 0.565$, $p < 0.001$). No correlation was found between LVEDP and other parameters, such as age, LAVI, LVMI, and PFR/EDV (Table 3). In further multivariable linear regression analyses, E/e' ($\beta = 0.547$, $p = 0.001$), %T-PFR ($\beta = 0.372$, $p = 0.024$), and LDSR ($\beta = -0.471$, $p = 0.006$) were independently associated with invasively measured LVEDP (Table 4). The associations between E/e', %T-PFR, LDSR, and LVEDP are shown in Fig. 2. Results of the receiver operating characteristic curve analysis applied to identify the optimal cutoff point for predicting LVEDP > 16 mmHg are depicted in Figs. 3 and 4. The sensitivity and specificity of E/e', %T-PFR, and LDSR for predicting the elevated LVEDP were 76%, 92%; 88%, 69%; and 76%, 89%, respectively.

Reproducibility

The ICCs for intra-observer reproducibility of %T-PFR and LDSR were 0.96 (95% CI, 0.922–0.974) and 0.95 (95% CI, 0.918–0.973), whereas the ICCs for interobserver reproducibility of these two parameters were 0.88 (95% CI, 0.788–0.931) and 0.94 (95% CI, 0.893–0.965).

Discussion

The present study validated CMR parameters for the estimation of LVEDP to identify HFpEF patients and compare their accuracy to echocardiographic indices. Firstly, CMR-derived time-volume curve revealed marked differences in PFR/EDV, T-PFR, and %T-PFR between patients with and without HFpEF. Secondly, CMR-derived LV global strain rates were significantly lower in HFpEF patients. Thirdly, not only the echocardiography assessed E/e' but also the CMR-derived %T-PFR and LDSR were correlated well with LVEDP measured by left heart catheterisation. To the best of our knowledge, the association between invasively measured intracardiac pressures with CMR parameters has not been sufficiently established in patients with HFpEF before.

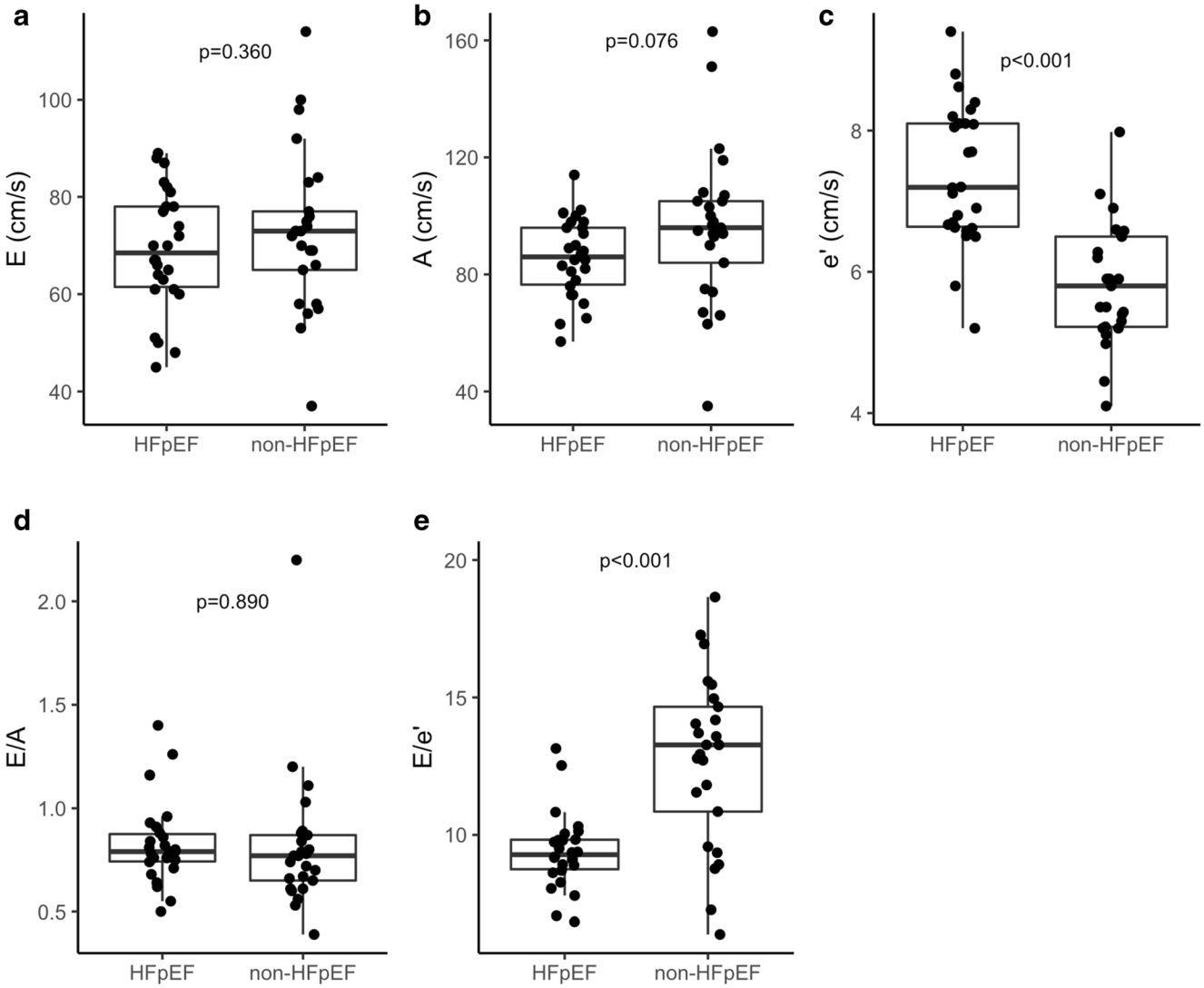

Fig. 1 Echocardiographic measurements between HFpEF and non-HFpEF patients. (**a**–**e**) E, A, e', E/A, and E/e' values between HFpEF and non-HFpEF patients. E, early diastolic mitral valve inflow; A, late diastolic mitral valve inflow; e', early diastolic tissue velocity; E/A, ratio of early diastolic mitral valve inflow to late diastolic mitral valve inflow; E/e', ratio of early diastolic mitral valve inflow to early diastolic tissue velocity

Evaluation of LV diastolic function by CMR-derived time-volume curve parameters

Notably, no echocardiographic E/A ratio differences were observed between patients with and without HFpEF in this study. The main underlying reason for this was that the gradual increase of LVEDP might reach the point of atrial contraction which could minimally contribute to the filling, so that HFpEF patients presented pseudonormal patterns. Besides, echocardiographic measurements depend on imaging plane orientation, which may not always be in the direction of flow or LV wall motion, resulting in systematic underestimation of inflow or tissue velocity [12]. The fact that the E/A ratio can neither be used to identify HFpEF patients nor correlate with LVEDP was in line with what we know. That is why the current guidelines suggest starting with E/e' in diagnostic procedure during diastolic dysfunction [4]. In contrast to echocardiography, LV time-volume curve obtained by CMR cine images depicts continuous dynamic changes of LV volume over time and can quantitatively and objectively assess PFR and T-PFR. Hieda et al [13] found that HFpEF patients had lower PFR/EDV, prolonged T-PFR, and increased %T-PFR, which were in parallel with our results. These data demonstrated that the extent of relaxation during early diastole may be insufficient in HFpEF patients. Furthermore, Mendoza et al [6] demonstrated that PFR was increased with the grade of diastolic dysfunction and found a relationship between PFR and E/e'.

E/e' and LVEDP

Echocardiographic E/e' > 10.8 demonstrated a sensitivity and specificity of 76% and 92% in identifying patients with

Table 2 CMR Parameters of left ventricular function and strain

Variables	Non-HFpEF ($n = 26$)	HFpEF ($n = 25$)	p value
LV function			
LVEF (%)	60 ± 5	59 ± 7	0.681
LVEDVI (mL/m^2)	58.2 ± 10.0	62.2 ± 10.8	0.175
LVESVI (mL/m^2)	23.6 ± 6.3	25.5 ± 7.2	0.312
LAVI (mL/m^2)	35.6 ± 11.7	45.7 ± 11.8*	0.004
LVMI (g/m^2)	45.1 ± 6.5	48.1 ± 9.2	0.191
PFR (mL/s)	0.253 ± 0.063	0.222 ± 0.066	0.095
PFR/EDV (s^{-1})	2.6 ± 0.8	2.1 ± 0.8*	0.027
T-PFR (ms)	423 ± 83	504 ± 41*	< 0.001
%T-PFR (%)	50.6 ± 8.7	60.8 ± 8.4*	< 0.001
PFV (mL)	26.6 ± 6.4	28.9 ± 10.2	0.339
Strain parameters			
LDSR (s^{-1})	0.93 ± 0.23	0.61 ± 0.15*	< 0.001
CDSR (s^{-1})	1.07 ± 0.24	0.90 ± 0.24*	0.016
RDSR (s^{-1})	− 3.37 ± 1.14	− 2.63 ± 1.05*	0.021

HFpEF heart failure with preserved ejection fraction, *LV* left ventricular, *LVEF* left ventricular ejection fraction, *LVEDV* indexed left ventricular end diastolic volume, *LVESVI* indexed left ventricular end-systolic volume, *LAVI* indexed left atrial volume, *LVMI* indexed left ventricular mass, *PFR* peak filling rate, *T-PFR* time to peak filling rate, *%T-PFR* the ratio of time to peak filling rate and cardiac cycle, *PFV* peak filling volume, *LDSR* global peak longitudinal diastolic strain rate, *CDSR* global peak circumferential diastolic strain rate, *RDSR* global peak radial diastolic strain rate

*$p < 0.05$

Table 3 Correlation of LVEDP with echocardiographic and CMR parameters

Variables	r	p value
Age	0.190	0.181
LVMI	0.205	0.150
LAVI	0.247	0.080
E/e'	0.504	< 0.001
PFR/EDV	0.217	0.126
T-PFR	0.285	0.043
%T-PFR	0.381	0.006
LDSR	0.565	< 0.001

LVMI indexed left ventricular mass, *LAVI* indexed left atrial volume, *PFR/EDV* ratio of peak filling rate and left ventricular end diastolic volume, *E/e'* ratio of early diastolic mitral valve inflow to early diastolic tissue velocity, *T-PFR* time to peak filling rate, *%T-PFR* the ratio of time to peak filling rate and cardiac cycle, *LDSR* global peak longitudinal diastolic strain rate

LVEDP > 16 mmHg in this study. Whether E/e' was a reliable estimation of LV, filling pressures remained controversial, though it was recommended by ASE guidelines [4]. A recent meta-analysis of 24 studies revealed that insufficient E/e' could estimate LVEDP, with low sensitivity (36%) and moderate specificity (83%) [14]. Furthermore, another two multicentre studies have drawn the conclusions that the correlations between E/e' and LVEDP were 0.34 and 0.65, respectively [15, 16]. Due to the fact that the e' was acquired at the level of mitral annulus, its accuracy can be compromised if regional dysfunctions are present. Furthermore, e' reflects the displacement of a single LV segment, and was frequently affected by preload during the situation of normal or enhanced LV relaxation. It is also involved in mitral valve diseases and annular calcification in the majority of HFpEF population, especially in elderly people. Moreover, the existence of a 'grey zone' between 8 and 15 was considered a limitation for its application in clinical practice. However, Watanabe et al [17] clarified that septal E/e' > 11.7 had a really high sensitivity and specificity of 87% and 93%, respectively. Lam et al [18] analysed 808 consecutive patients and found that a sensitivity and specificity of 70% and 85% when septal E/e' > 12.5. These E/e' cutoff values were a little higher than this study, which might probably be due to the fact that the e' was evaluated from septal e', while e' in our study was measured as the average value of septal and lateral e'. In line with these studies, our study also demonstrated that E/e' was correlated well with invasively measured LVEDP.

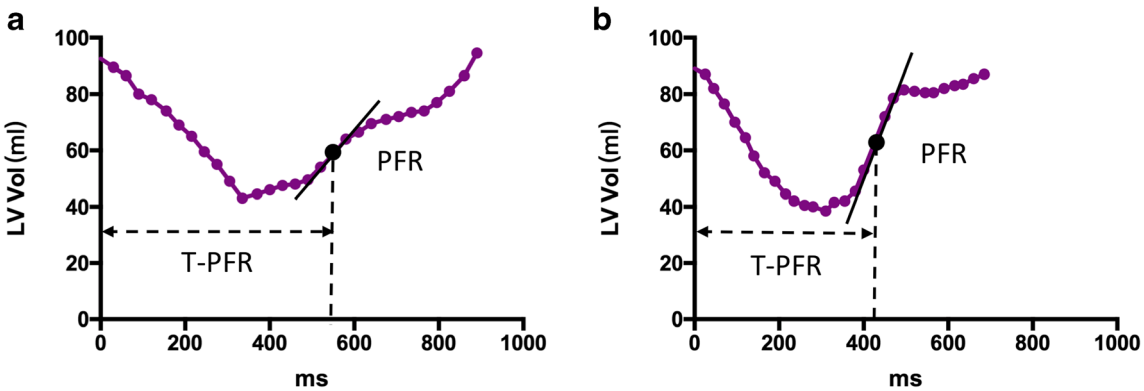

Fig. 2 Time-volume curve depicted by CMR. **a** LV time-volume curve in a HFpEF subject. Peak filling rate (PFR) is derived from the steepest gradient in the curve in the early diastolic phase. The horizontal dotted line demonstrates time to peak filling rate (T-PFR). PFR is lower while T-PFR is longer in HFpEF subject. **b** LV time-volume curve in a non-HFpEF subject

Table 4 Predictors of LVEDP using multiple linear regression analysis

Variables	β	*t*	*p* value
E/e'	0.547	3.912	0.001
T-PFR	− 0.256	− 1.465	0.156
%T-PFR	0.372	2.413	0.024
LDSR	− 0.471	− 2.998	0.006

E/e' ratio of early diastolic mitral valve inflow to early diastolic tissue velocity, *T-PFR* time to peak filling rate, *%T-PFR* the ratio of time to peak filling rate and cardiac cycle, *LDSR* global peak longitudinal diastolic strain rate

LDSR and LVEDP

Different from E/e', strain rate was derived from all myocardial segments and undoubtedly reflected LV global performance index. Wang and his colleagues [19] were the first to apply global diastolic strain as a novel assessment to predict LV relaxation and filling pressure non-invasively in both animal models as well as human beings. Morris et al [20] found that the addition of 2D speckle tracking LV longitudinal diastolic strain rate into the current evaluation of LV diastolic dysfunction model could significantly increase the veracity from 14.3 to 33.2%. The authors also proposed that an abnormal LV diastolic strain rate level showed a significant association with the risk of HF hospitalisation in the coming 2 years. These findings illustrated the fact that the diastolic strain rate was not only a reliable diagnostic parameter that correlated well with LVEDP but also a promising prognostic index related to the event of HFpEF patients. Favourable reproducibility also indicated that CMR-derived robust parameters should be evaluated prospectively in new studies. The associations between invasively measured intracardiac pressures with CMR parameters have not been established in HFpEF patients until being stated in this study. Intriguingly, the results of our study confirmed that the CMR-derived LDSR shared

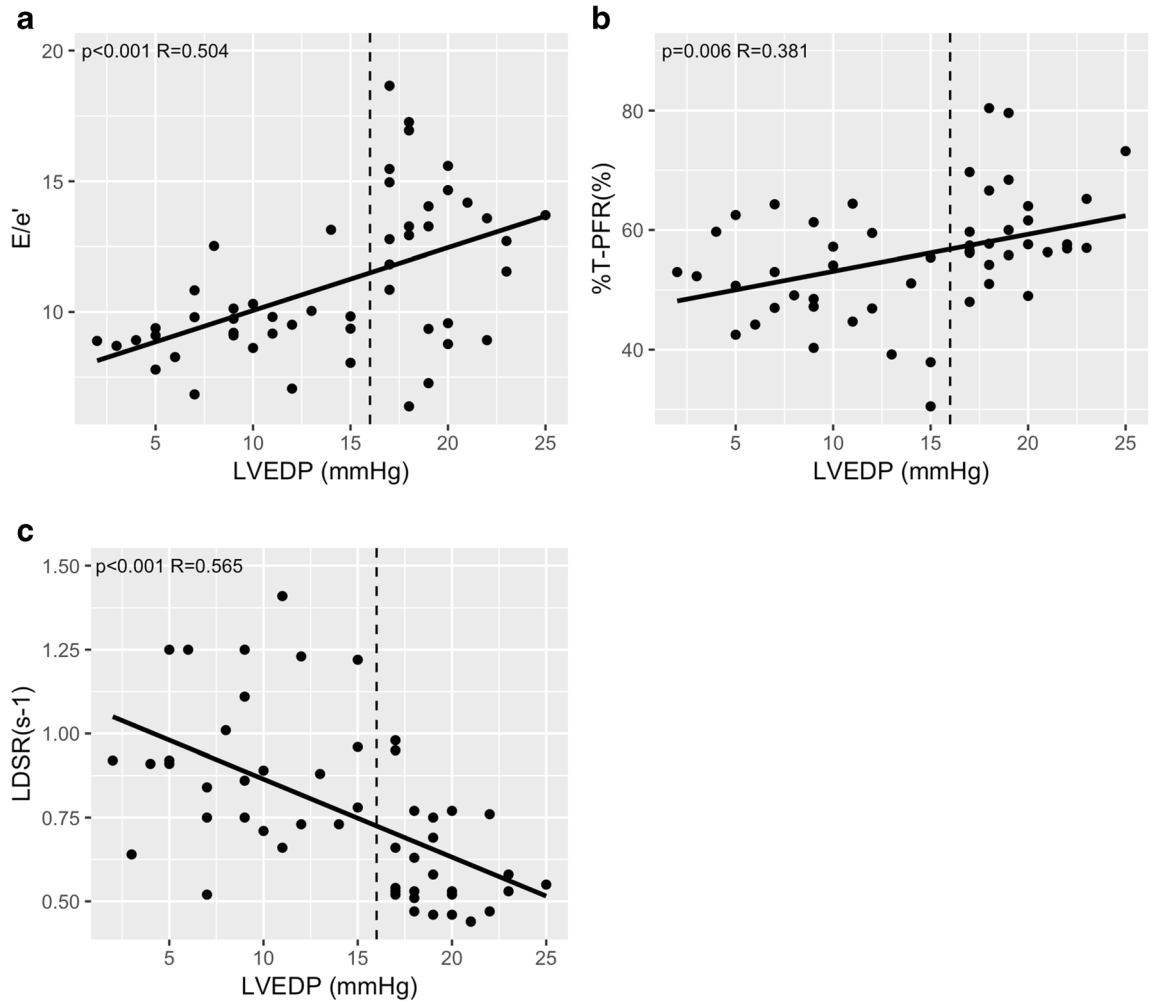

Fig. 3 Correlations of E/e', %T-PFR, LDSR, and LVEDP. **a** Significantly positive correlation between LVEDP and echocardiography assessed E/e' ($r = 0.504$, $p < 0.001$). **b** Significantly positive correlation between LVEDP and CMR-derived %T-PFR ($r = 0.381$, $p = 0.006$). **c** Significantly inverse correlation between LVEDP and CMR-derived LDSR ($r = 0.565$, $p < 0.001$). The vertical line was placed on each plot at an LVEDP value of 16 mmHg

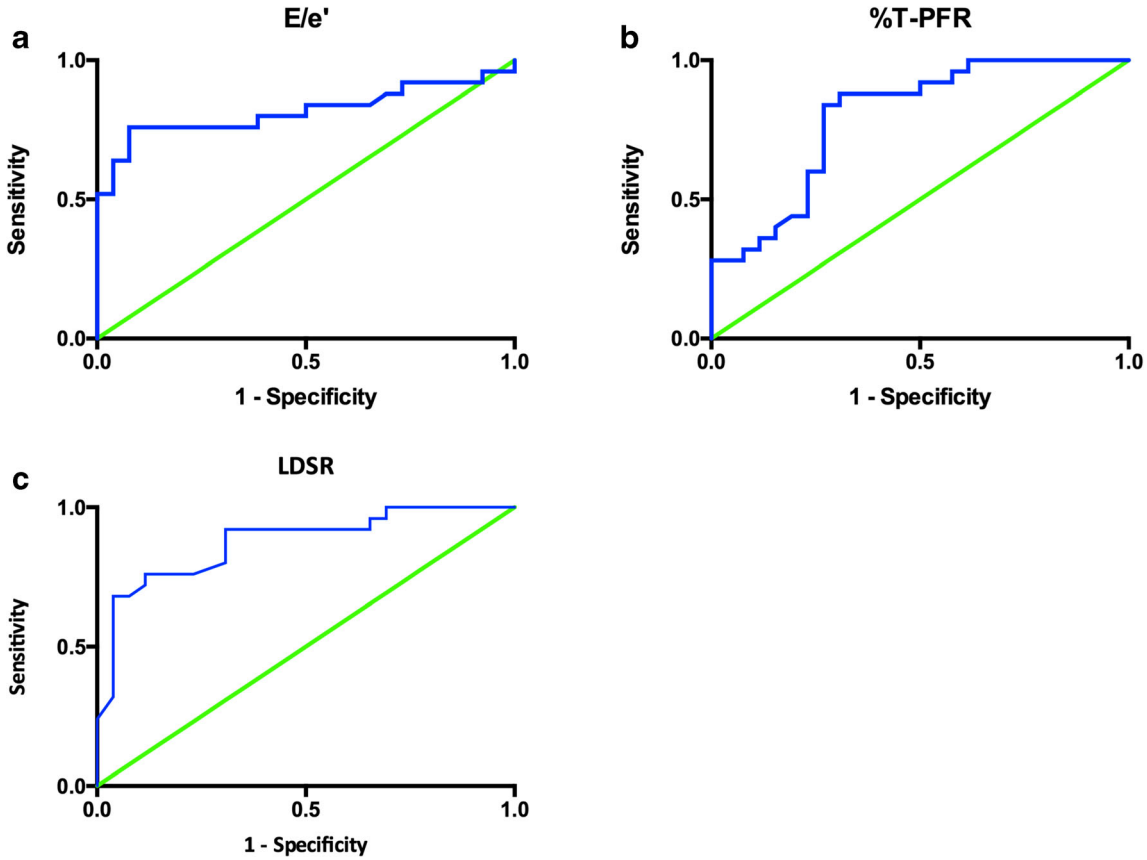

Fig. 4 Receiver operating characteristic curve analysis of E/e', %T-PFR, and LDSR. The cutoff point of E/e', %T-PFR, and LDSR for predicting LVEDP > 16 mmHg was 10.8, 54.1%, and 0.7(s-1), respectively. The area under curve (AUC) of E/e', %T-PFR, and LDSR were 0.82 (95% CI, 0.690–0.947), 0.80 (95% CI, 0.675–0.920), and 0.88 (95% CI, 0.777–0.972), respectively

conformity with echocardiographic data and was as well independently correlated with LVEDP. The clinical applications of this study presented mainly two aspects: (1) information about diastolic function has been added to complete the interpretation of CMR evaluation in heart function and (2) several parameters of CMR in this study could be particularly useful in cases when the echocardiographic application is limited (such as mitral prosthesis, mitral calcification, and wall motion abnormalities).

Study limitations

Our study has some limitations that need to be considered. Firstly, as a single-centre study, the sample size was not big enough. A multicentre study may be helpful to validate our results. Secondly, compared with conventional LV diastolic measurements, LDSR is not a handy and well-known parameter and needs to be additionally analysed offline. Thirdly, limited temporal resolution for CMR may affect the ability to interpret diastolic function. Extending the scanning time and collecting more than one complete cardiac cycle were methods adopted in this study. Further studies are warranted to confirm the association between LDSR and long-term outcomes of patients with HFpEF.

Conclusions

In summary, this study demonstrated that not only the echocardiographic E/e' but also CMR-derived time-volume curve parameters and diastolic strain rate indices were correlated with invasive LVEDP obtained by left heart catheterisation. CMR parameters put forward clinical implications on the identification of HFpEF patients. Further studies are warranted to confirm whether CMR can be used to guide therapeutic management and stratify clinical outcomes for HFpEF patients.

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Compliance with ethical standards

Guarantor The scientific guarantor of this publication is Jingwei Pan.

Conflict of interest The authors of this manuscript declare no relationships with any companies, whose products or services may be related to the subject matter of the article.

Statistics and biometry No complex statistical methods were necessary for this paper.

Informed consent Written informed consent was obtained from all subjects (patients) in this study.

Ethical approval Institutional Review Board approval was obtained.

Methodology
- perspective
- observational
- performed at one institution

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