



Regional strain patterns in patients with mitral valve prolapse

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Abstract

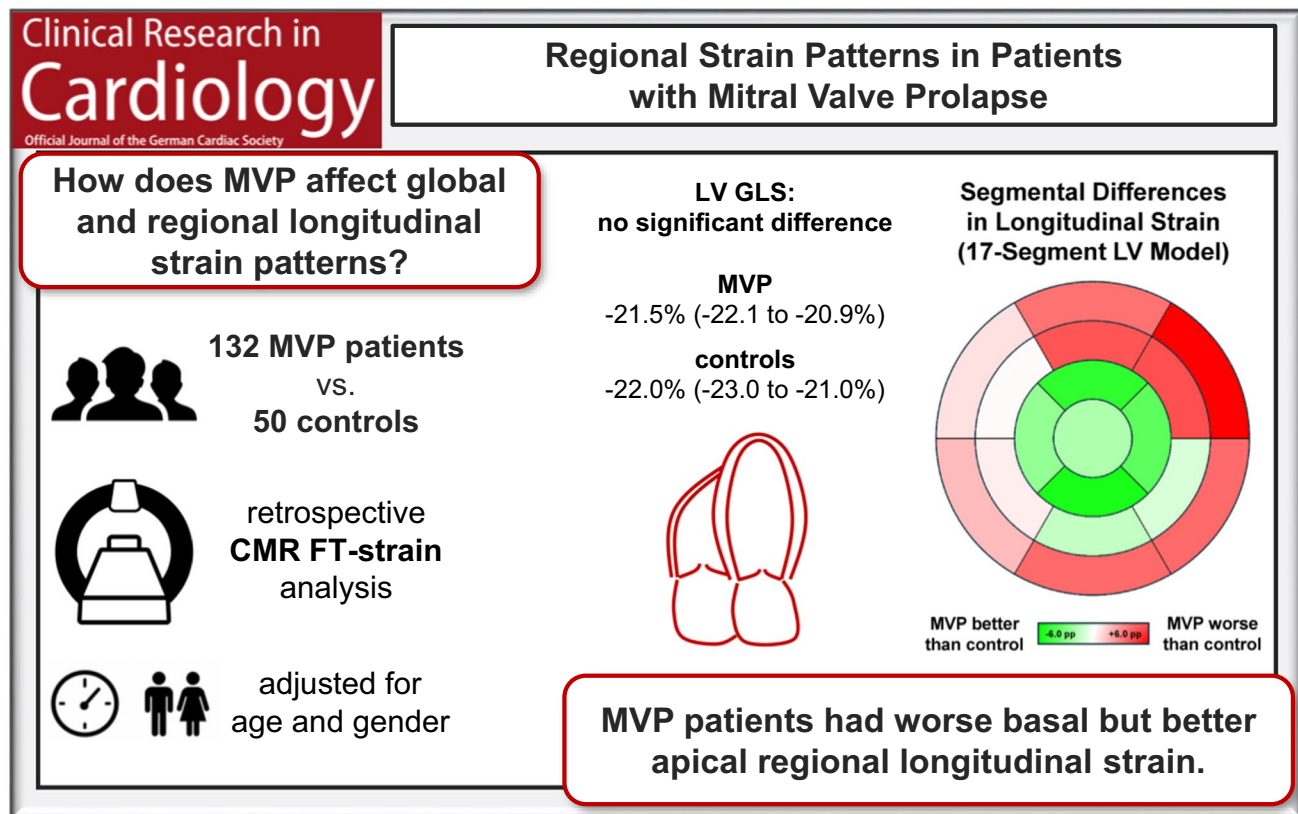
Purpose Echocardiographic studies have shown that patients with mitral valve prolapse (MVP) exhibit altered regional contraction patterns. With cardiovascular magnetic resonance (CMR) becoming increasingly important in the evaluation of global and regional cardiac function, we aimed to quantify the regional contraction patterns of patients with MVP using CMR feature tracking (FT) strain analysis in comparison to a control group.

Methods Of all patients who underwent CMR scans from 2013 to 2022 at our institution, 132 patients with MVP were identified and compared to 50 controls without any cardiac condition. CMR scans were performed on 1.5-T and 3-T scanners, and CMR-FT strain analysis was performed on cine images using MEDIS QStrain 4.1. The primary endpoints were regional peak left ventricular (LV) longitudinal strain values. Secondary endpoints included LV global circumferential strain (GCS) and global longitudinal strain (GLS) and left atrial (LA) reservoir strain and right ventricular (RV) free wall longitudinal strain. Differences between groups were assessed using linear regression models, adjusting for age and sex.

Results Patients with MVP showed worse regional peak longitudinal strain compared to controls in the basal and part of the medial LV segments, especially in segments S1, S4, S6, S7, and S12. In contrast, the apical segments S13, S14, S15, and S16 showed better strain values. Additionally, LA reservoir strain was reduced in MVP patients. LV GCS, LV GLS, and RV free wall longitudinal strain were similar between both groups.

Conclusion While patients with MVP showed preserved LV GCS and GLS compared to controls, LV regional longitudinal strain analysis showed impaired strain in the basal segments and increased strain in the apical segments.

Clinical Research in Cardiology – Graphical Abstract



Keywords Mitral valve prolapse · Strain · Feature tracking · Cardiac magnetic resonance imaging

Abbreviations

BMI	Body mass index
bSSFP	Balanced steady-state free precession
CI	Confidence interval
CMR	Cardiac magnetic resonance
FT	Feature tracking
GCS	Global circumferential strain
GLS	Global longitudinal strain
LA	Left atrial
LGE	Late gadolinium enhancement
LS	Longitudinal strain
LV	Left ventricular
LVEDVi	Left ventricular end-diastolic volume index
LVEF	Left ventricular ejection fraction
LVESVi	Left ventricular end-systolic volume index
LVSVi	Left ventricular stroke volume index
MAD	Mitral annular disjunction

MVP	Mitral valve prolapse
NCCM	Noncompaction cardiomyopathy
pp	Percentage points
RV	Right ventricular
S	Segment
SD	Standard deviation
STE	Speckle tracking echocardiography
TTE	Transthoracic echocardiography

Introduction

Despite its first description more than 100 years ago and the high prevalence of 2–3%, the genesis, pathophysiology, and prognostic factors of mitral valve prolapse (MVP) are still insufficiently researched [1–3]. MVP is defined as an end-systolic prolapse of the anterior, posterior, or

both mitral valve leaflets into the atrium. This condition generally has a favorable prognosis, but some patients with MVP may develop a significant mitral valve regurgitation or ventricular arrhythmias [4, 5].

The primary form of MVP can be divided into the classical and the nonclassical phenotype. The classical phenotype, also known as Barlow's disease, is characterized by thickened leaflets due to myxomatous infiltration and bileaflet prolapse, whereas the nonclassical phenotype is associated with leaflet thinning caused by reduced connective tissue production [6, 7].

Several genes (FLNA, DCHS1, DZIP1, and PLD1) with different inheritance patterns have been identified as associated with MVP, indicating a familial component in the pathophysiology of this valvular disease [8–11]. In particular, the presence of FLNC mutations seems to be associated with a higher risk of arrhythmogenic complications [12]. However, the role of these genes in the development of MVP and its genetic mechanisms remains incompletely understood.

Echocardiographic observations have shown that the regional contraction patterns are altered in patients with MVP, despite a normal global ejection fraction [13, 14]. Knowledge of these patterns is important, as they may be mistaken for wall motion abnormalities caused by other cardiac diseases and might provide further insights into the occurrence of adverse events in MVP. Regional myocardial function can be quantified using strain analysis. Cardiac magnetic resonance (CMR) has emerged as the reference standard for assessing both global and regional cardiac function, with CMR feature tracking (FT) as a commonly used CMR-based strain analysis [15]. CMR-FT requires only standard CMR sequences and can be retrospectively applied to existing CMR scans. FT-derived left ventricular (LV) global longitudinal strain (GLS) and regional longitudinal strain also have shown excellent intra- and interobserver reproducibility [16, 17].

Previous studies investigating CMR-FT strain in patients with MVP showed inconclusive results. Romero Daza et al. in 2021 reported better regional longitudinal and circumferential strain in the basal segments of the LV in patients with MVP compared to controls, while LV global circumferential strain (GCS) did not differ between both groups and LV GLS was marginally better in MVP patients [18]. Guglielmo et al. in 2021 found slightly reduced LV GLS, LV GCS, and LV radial strain in MVP patients with moderate to severe mitral insufficiency compared to controls but did not report segmental strain values [19]. A second study by Guglielmo et al., published in 2023 after the beginning of our analysis, found impaired longitudinal strain, especially of the inferior and inferolateral basal wall and a slightly reduced LV global longitudinal strain in MVP patients compared to controls without MVP [20]. Other studies using echocardiography-based speckle tracking strain analysis showed an impaired

regional longitudinal strain in the basal segments [14] and lower LV GLS and weaker contraction in the inferior and lateral wall [13]. However, it should be noted that these studies were based on small study populations with varying methods and strain analysis was often not the primary focus of the research. Importantly, speckle tracking echocardiography (STE) and CMR-FT rely on different technical principles for strain evaluation, meaning that strain values derived from these modalities are not directly comparable [21]. Therefore, CMR-FT represents a methodologically independent approach, and CMR-derived regional strain data in MVP patients remain scarce.

Structural and mechanical abnormalities in the basal segments caused by MVP, like systolic curling and mitral annular disjunction (MAD), are known to influence myocardial mechanics. A key motivation for this study was to improve understanding of how these MVP-specific conditions are reflected in CMR-FT-derived strain measurements. This would facilitate the interpretation of regional strain abnormalities in clinical practice and help differentiate prolapse-related mechanical effects from true myocardial dysfunction. This study aimed to quantify this effect using CMR-FT in a well-defined cohort of otherwise healthy MVP patients, compared to controls without apparent heart disease. Beyond the basal segments, the goal was also to characterize global and regional longitudinal endocardial strain patterns across all LV segments, the right ventricle, and the left atrium in a large study population.

Methods

Study population

Patients who underwent CMR imaging at our institution between January 1, 2013, and December 31, 2022, were included in this retrospective study if the cine images demonstrated the presence of MVP. In patients with multiple examinations, the first was analyzed. Mitral valve prolapse was defined as prolapse of either the anterior or the posterior leaflet more than 2 mm above the level of the valve in the three-chamber view (Fig. 1) [22]. Control data were derived from individuals without apparent heart disease who had volunteered for five previous prospective studies (Table S1) and underwent CMR imaging as part of those studies at our institution between 2017 and 2022. The CMR images of the examinations were reviewed to ensure an absence of MVP.

Exclusion criteria for both patients and controls were younger than 18 years, coronary heart disease, moderate or severe valvular disease described in the report, myocardial wall thickness > 15 mm, left ventricular ejection fraction (LVEF) < 50%, history of myocardial infarction or myocarditis, persistent atrial fibrillation, congenital heart disease,

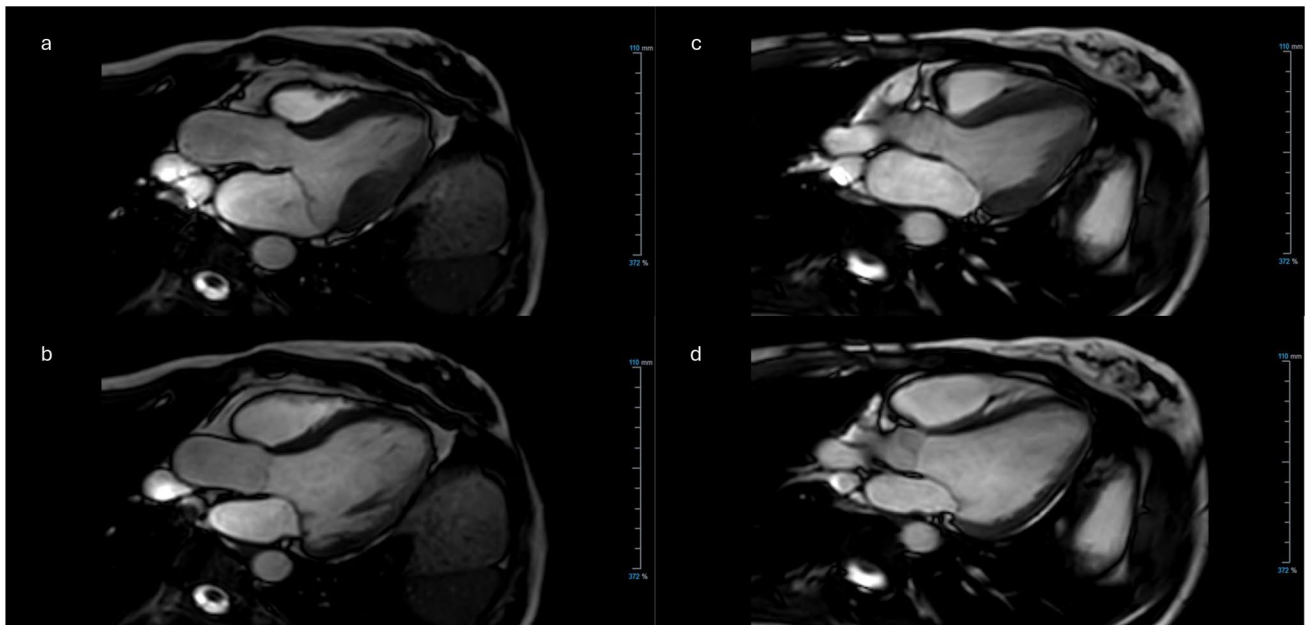


Fig. 1 CMR images of a patient with MVP in end-systolic (a) and end-diastolic phase (b) and CMR images of a control without MVP in end-systolic (c) and end-diastolic phase (d). CMR cardiac magnetic resonance, MVP mitral valve prolapse

prior cardiac surgery or cardiac ablation, aortic ectasia, or prior aortic surgery. The digital patient records at our institution were reviewed to determine any comorbidities.

The sample size estimation was based on an unpaired *t* test with a significance level of 0.05, assuming a difference of +2 percentage points (pp) of the regional longitudinal strain of the basal inferolateral segment between patients with MVP and controls, based on echocardiography-derived data that were available at the time [13], and a common standard deviation of 4 pp. It showed that a minimum of 100 patients and 50 controls would achieve a power > 80% to detect the expected difference.

This study was approved by the local ethics committee (Application EA4/099/23). Informed consent was waived for this retrospective study.

CMR imaging

CMR scans were performed on 1.5-T (Achieva and Ingenia Ambition X, Philips Healthcare, Best, The Netherlands) and 3-T (Ingenia, Philips Healthcare, Best, The Netherlands) scanners with multielement phased-array coils. Cine images were acquired using retrospectively gated balanced steady-state free precession (bSSFP) sequences. Planning of the acquisitions was performed in accordance with standard CMR protocol recommendations [23]. Following transaxial, coronal, and sagittal survey images, vertical and horizontal long axis cine scout images were acquired. The short axis

was aligned perpendicular to the long axis scout images. The four-chamber view was aligned perpendicular to the short axis and rotated to cut through the LV apex, the center of the mitral valve, and the RV angle, avoiding the aortic bulb. The two-chamber view was aligned along the long axis using the four-chamber view and then rotated to cut through the anterior and inferior wall using the short axis. Typical scan parameters at 1.5 T were $1.6 \times 1.6 \times 6$ to $1.8 \times 1.7 \times 8$ mm voxel size, sense factor 2, TE 1.58 ms, and TR 3.2 ms. At 3 T, typical scan parameters were $1.9 \times 1.8 \times 6$ –8 mm voxel size, sense factor 2, TE 1.49 ms, and TR 3.0 ms.

CMR analysis

LV volumetry was taken from the imaging reports and was initially obtained by contouring of end-systolic and end-diastolic LV endocardium in the short-axis cine images, including papillary muscles in LV volumes, and calculated using the summation-of-discs method according to Simpson's rule. CMR-FT endocardial strain analysis was performed semiautomatically using QStrain 4.1 (Medis, Leiden, The Netherlands), as described previously [15]. LV GCS and GLS as well as peak regional longitudinal strain of all 17 segments of the LV were assessed on two-, three-, and four-chamber view cine images, with peak strain defined as maximum strain of the segment during the cardiac cycle. Additionally, two-chamber view cine images were used to calculate left atrial (LA) reservoir strain and

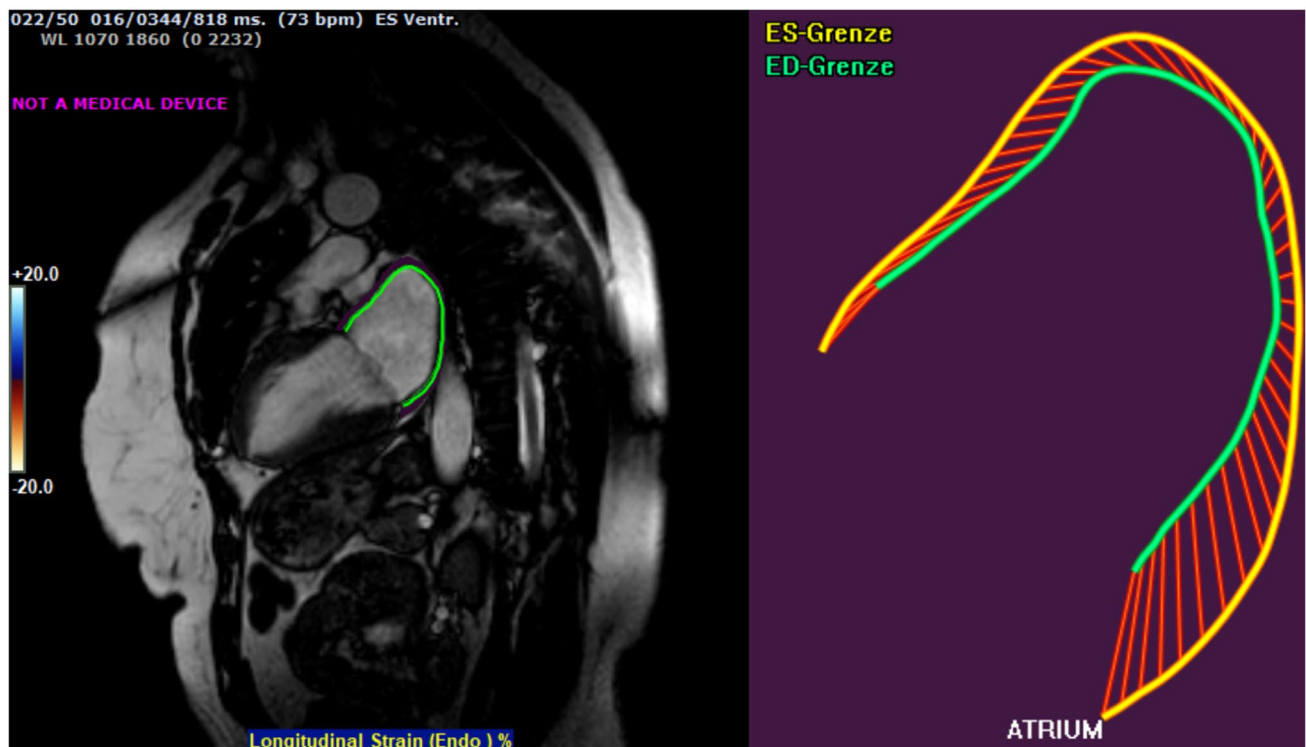


Fig. 2 Exemplary assessment of the left atrial global longitudinal strain in the two-chamber view (QStrain version 4.1, Medis, Leiden, The Netherlands). Left: overlay of atrial contours and cine two-cham-

ber view. Right: atrial contours in ventricular end-diastole (green) and end-systole (yellow) with connecting feature tracking lines (red)

four-chamber view cine images to calculate right ventricular (RV) free wall longitudinal strain (Figs. 2 and 3). We also evaluated the presence of curling, which refers to an abnormal systolic motion of the posterior mitral ring relative to the adjacent myocardium [24], and MAD. MAD was defined as separation of the posterior mitral annulus from the myocardium both in end-systole and end-diastole and was determined primarily using the three-chamber view. In cases of uncertainty, the two- and four-chamber views were also consulted to support the assessment. The distance of disjunction was measured in the three-chamber view.

Echocardiography analysis

Of our overall cohort, we identified those MVP patients who underwent transthoracic echocardiography (TTE) within 1 year before or after their CMR examination at our institution. After reviewing the images regarding quality and availability of the necessary views, 2D speckle tracking strain analysis was performed semiautomatically on the apical two-, three-, and four-chamber long-axis views using TTA2.51.04 (Tomtec Imaging Systems, Unterschleissheim, Germany) (Fig. 4).

Technical differences between CMR and echocardiography analysis

As already mentioned in the introduction, CMR-FT and STE are two different methods for strain measurement and the derived strain values can differ.

CMR-FT is based on detecting different grayscale patterns of the anatomic structures to correctly identify and track the endocardial and epicardial borders and hence the myocardial motion [25]. This method benefits from the relatively unrestricted access to a large field of view and the high signal-to-noise and contrast-to-noise ratios of the two-, three-, and four-chamber view cine images [26], which are planned based on anatomical landmarks [23]. Therefore, measurements are highly accurate and reproducible [26]. A weakness of CMR-FT is the temporal resolution. A CMR cine loop delivers 25 to 50 frames per heartbeat and is acquired over several cardiac cycles, which means that myocardial motions of short durations may not be accounted for, leading to a possible underestimation of strain values [26].

STE assesses the myocardial motion through tracking of speckles, which are stable acoustic markers within the myocardial tissue [25, 26]. It uses the apical two-, three-,

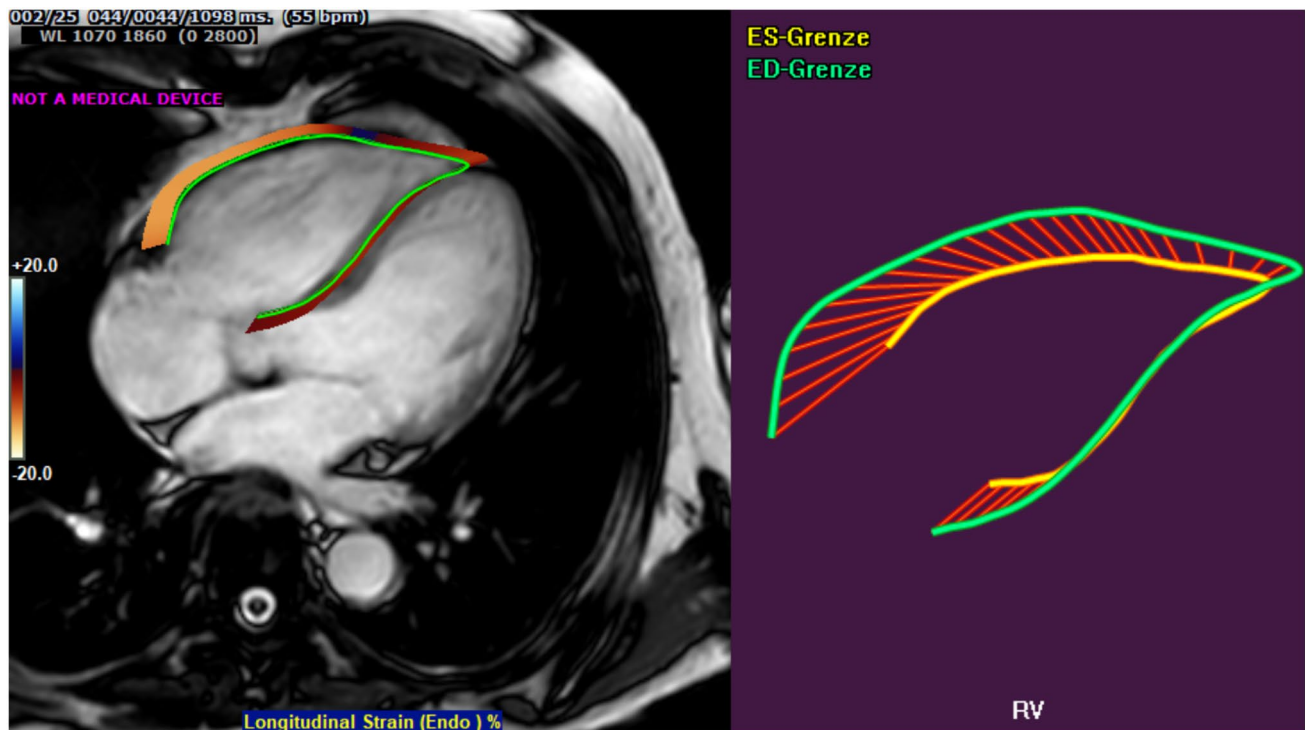


Fig. 3 Exemplary assessment of the right ventricular free wall strain in the four-chamber view (QStrain version 4.1, Medis, Leiden, The Netherlands). Left: overlay of right ventricular contours and cine

four-chamber view. Right: right ventricular contours in end-diastole (green) and end-systole (yellow) with connecting feature tracking lines (red)

and four-chamber long-axis views obtained by transducer rotation of approximately 60°. In theory, echocardiography images offer a great spatial resolution with a pixel size of about 0.3 mm and a great temporal resolution with a frame rate above 60 frames per second compared to CMR [26]. However, STE relies heavily on the image quality, which is often limited by the availability of an adequate acoustic window and the low signal-to-noise ratio [25, 26].

CMR-FT- and STE-derived global strain parameters, including GLS and GCS, show good correlation despite limited interchangeability, whereas regional strain measurements exhibit only moderate correlation [21, 27].

Statistical analysis

Baseline characteristics, standard CMR parameters, strain values, and strain value ratios were descriptively compared between patients and controls using absolute and relative frequencies for categorical and mean and standard deviation (SD) for continuous parameters. Differences in CMR parameters and strain values were derived from multivariable linear regression models, adjusted for age and sex as potential confounders. Where the assumptions for ordinary-least-squares regression were violated—judged based on residual plots—robust regression was applied instead. Based on these models, we derived the estimated

marginal means and adjusted differences between patients and controls, along with 95% confidence intervals (CIs). For the strain value ratio, data were logarithmically transformed prior to analysis and results were transformed back to the original scale.

Statistical analysis was performed using the R version 4.4.2 [28] and other R packages [29–35].

Results

Baseline parameters

In total, 132 patients with MVP were included in this study and compared to 50 controls without MVP (Fig. 5). There were fewer males with MVP than among the controls (40.9% vs. 60.0%), and patients with MVP were on average older than controls (mean 51.2 ± 16.4 vs. 39.6 ± 15.8 years). Overall, MVP patients had few comorbidities (Table 1).

Characteristics of MVP patients

The imaging characteristics of the mitral leaflets in MVP patients show a similar proportion of patients with bile-aflet and single leaflet prolapse (48 vs. 52%). In general,

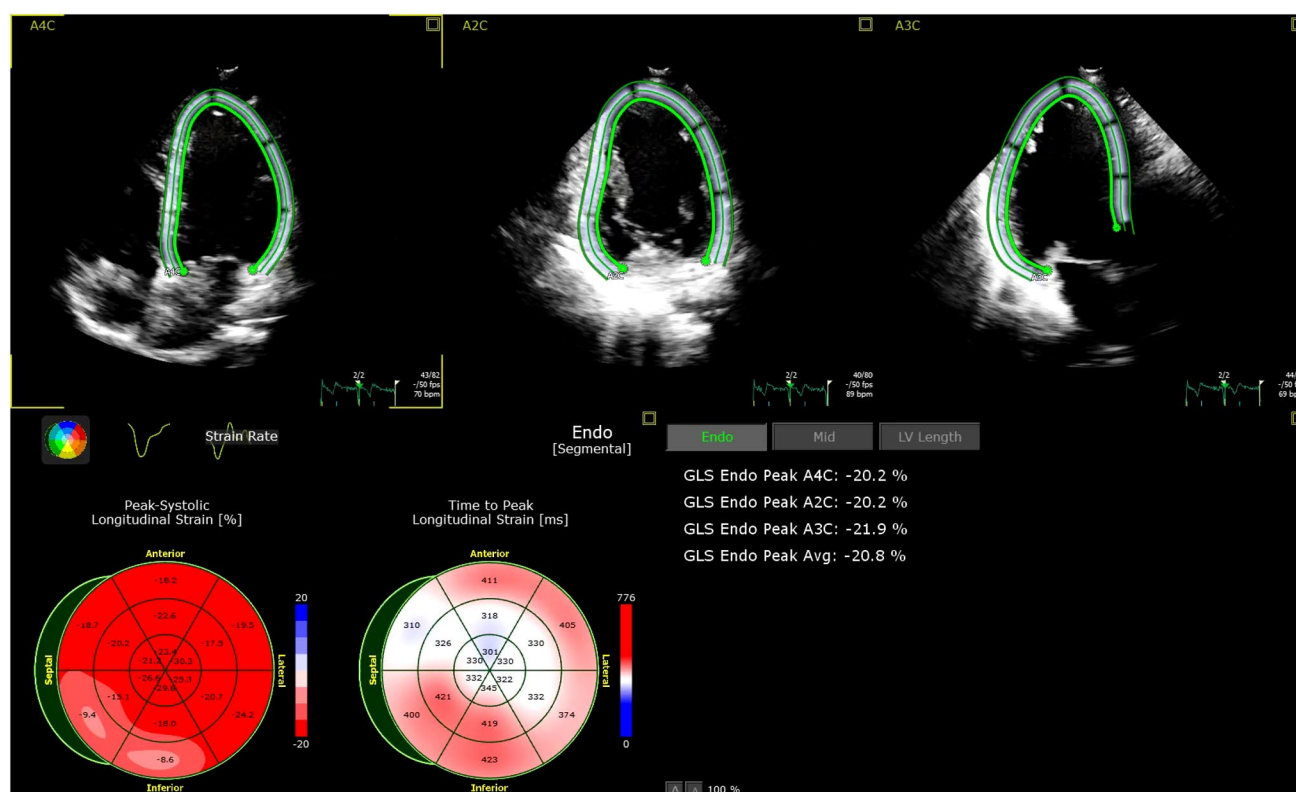


Fig. 4 Exemplary assessment of TTE-STE-derived strain (TTA2.51.04, Tomtec Imaging Systems, Unterschleissheim, Germany). TTE transthoracic echocardiography, STE speckle tracking echocardiography

the patient population showed a mild displacement of the mitral valves with an average prolapse distance of 4.4 ± 2.5 mm (Table 2). A majority of the MVP patients showed signs of curling (68%). One hundred fourteen of the 132 examined patients with MVP had an examination with contrast agent. Nineteen patients showed signs of local fibrosis, especially in the basal and medial inferior and inferolateral segments.

Standard CMR parameters

After adjusting for age and sex, patients with MVP had a higher left ventricular end-diastolic volume index (LVEDVi, adjusted difference $+15.8 \text{ ml/m}^2$ [95% CI, $+10.5$ to $+21.0$]), a higher left ventricular end-systolic volume index (LVESVi, $+8.4 \text{ ml/m}^2$ [$+5.6$ to $+11.1$]), and a higher left ventricular stroke volume index (LVSVi, $+6.9 \text{ ml/m}^2$ [$+3.7$ to $+10.1$]) (Table 3). Furthermore, patients with MVP showed a reduced LVEF (-3.0 pp [-4.8 to -1.2]) and a marginally thicker basal septal myocardial wall than the control group ($+1.2$ mm [$+0.6$ to $+1.7$]). The thickness of the basal lateral myocardial wall and the LA area were similar between patients and controls. Although T1 mapping was not performed in all patients and controls, patients with MVP

tended to show higher basal septal T1 values, which nevertheless remained within the normal reference range (Table 4).

Global CMR-FT strain values

Regarding global strain values, LV GLS ($+0.5$ pp [-0.7 to $+1.8$]), LV GCS ($+0.4$ pp [-1.3 to $+2.3$]), and RV free wall longitudinal strain (LS) (-0.3 pp [-2.6 to $+2.0$]) were comparable between MVP patients and controls after adjusting for age and sex (Table 3). Only LA reservoir strain showed a trend toward reduced values in MVP patients (-3.8 pp [-7.6 to $+0.1$]).

Regional CMR-FT strain values

Regarding regional longitudinal strain, patients with MVP showed less negative values than the control group in all basal LV segments (Table 5, Fig. 6). Additionally, the medial anterior segment also showed less negative strain values in MVP patients compared to controls. In contrast, MVP patients showed more negative strain values in the apical regions and the apex than the controls.

After adjusting for age and sex, the pattern remained similar (Table 5, Fig. 7). Longitudinal strain values remained less

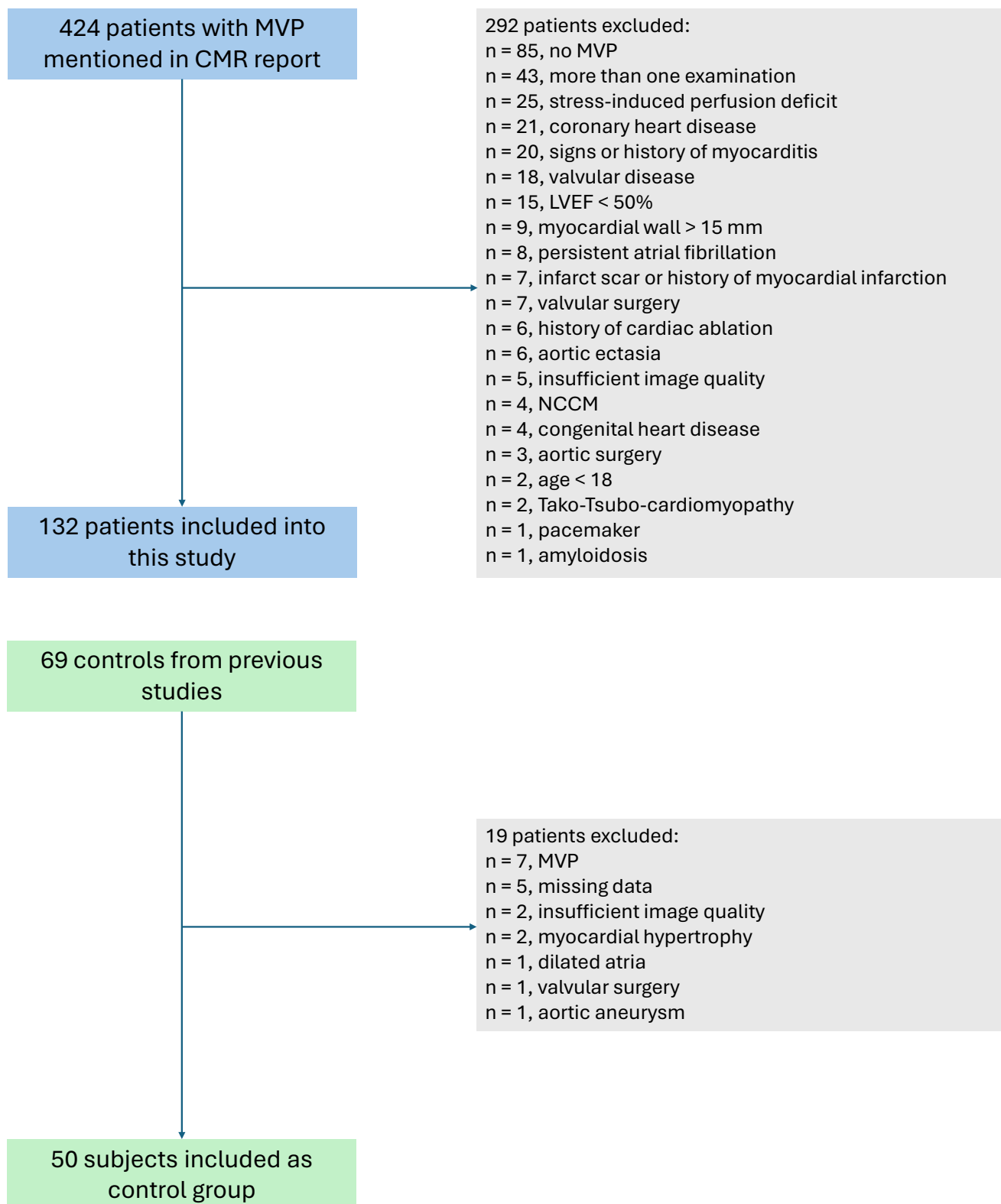


Fig. 5 Study flowchart of patient and control group. Reasons for exclusion from the study. CMR cardiac magnetic resonance, LVEF left ventricular ejection fraction, MVP mitral valve prolapse, NCCM noncompaction cardiomyopathy

Table 1 Baseline parameters of controls and patients with MVP

Parameter	Total (<i>n</i> = 182)	Controls (<i>n</i> = 50)	Patients with MVP (<i>n</i> = 132)
Age (years)	48 ± 17.0	39.6 ± 15.8	51.2 ± 16.4
Male sex (<i>n</i>)	84 (46%)	30 (60%)	54 (41%)
BMI (kg/m ²)	23.4 ± 3.8	23.9 ± 3.4	23.3 ± 3.9
Hypertension (<i>n</i>)	23 (13%)	4 (8%)	19 (14%)
Diabetes mellitus (<i>n</i>)	4 (2%)	1 (2%)	3 (2%)
Dyslipidemia (<i>n</i>)	11 (6%)	3 (6%)	8 (6%)
Paroxysmal AF (<i>n</i>)	5 (3%)	0 (0%)	5 (4%)
Field strength 1.5 T (<i>n</i>)	95 (52%)	21 (42%)	74 (56%)
Field strength 3 T (<i>n</i>)	87 (48%)	29 (58%)	58 (44%)

Data as mean ± standard deviation or *n* (%)

MVP mitral valve prolapse, BMI body mass index, AF atrial fibrillation

Table 2 Mitral valve characteristics of the MVP patients

Characteristics	Patients with MVP (<i>n</i> = 132)
Bileaflet prolapse (<i>n</i> , %)	63/132 (48%)
Single leaflet prolapse (<i>n</i> , %)	69/132 (52%)
- Anterior leaflet prolapse (<i>n</i> , %)	11/69 (16%)
- Posterior leaflet prolapse (<i>n</i> , %)	58/69 (84%)
Prolapse distance (mm, mean ± SD)	4.4 ± 2.5
Presence of curling (<i>n</i> , %)	90/132 (68%)
Presence of MAD (<i>n</i> , %)	43/132 (33%)
MAD distance (mm, mean ± SD)	4.0 ± 2.1
Nonischemic LGE of the LV ^a (<i>n</i> , %)	19/114 (17%)

MVP mitral valve prolapse, SD standard deviation, MAD mitral annular disjunction, LGE late gadolinium enhancement, LV left ventricle

^aOnly 114 of the 132 MVP patients underwent an examination with contrast agent

negative in MVP patients in the basal LV segments, especially in the basal anterolateral (+ 6.0 pp [+ 3.1 to + 9.0]), basal inferior (+ 3.5 pp [+ 0.7 to + 6.4]), and basal anterior segment (+ 3.3 pp [+ 0.7 to + 5.8]), while all apical segments continued to show more negative strain values in MVP patients, with the notable finding that the difference in the apical septal segment (− 2.5 pp [− 4.7 to − 0.2]) is less pronounced compared to the apical inferior (− 5.4 pp [− 8.6 to − 2.3]), the apical anterior (− 4.9 pp [− 8.5 to − 1.4]), and the apical lateral segment (− 3.8 pp [− 6.9 to − 0.8]). Regarding the medial LV segments, the medial anterior segment (+ 4.0 pp [+ 1.3 to + 6.7]) and the medial anterolateral

segment (+ 4.1 pp [+ 0.8 to + 7.4]) of MVP patients stand out with less negative strain values compared to healthy controls, while the strain values of the other medial segments were similar in both groups. The latter also applied to the apex.

As the lateral segments seemed to be more affected than the other myocardial regions, we analyzed the strain ratio between the basal anterolateral (S6) and the apical lateral (S16) segment (Table 6). We selected the basal anterolateral segment due to the largest observed difference. The S6/S16 strain ratio of MVP patients was lower than the control group (geometric mean 1.26 ×/÷ 1.90 vs. 1.84 ×/÷ 1.68). The difference remained after adjusting for age and sex using a multivariable linear regression model (estimated marginal mean 1.32 [95% CI, 1.13 to 1.54] vs. 1.84 [1.58 to 2.33]). MVP patients with MAD showed a slightly higher strain ratio than patients without MAD (1.46 [1.17 to 1.82] vs. 1.26 [1.06 to 1.49]). The presence of curling or myocardial fibrosis however was not associated with differences in the S6/S16 strain ratio.

TTE-STE strain values

Of the overall cohort, 19 MVP patients and 9 controls underwent both CMR and echocardiography examination and were therefore included in this subgroup analysis. Due to the tertiary care level of our center, the majority of patients referred for CMR had their TTE performed outside of our clinic and TTE images were available only for a small subset of patients. After adjusting for age and sex, the GLS showed no relevant difference between MVP patients and controls (+ 0.7 pp [− 3.1 to + 4.5]).

Analysis of the regional strain values revealed a pattern similar to that observed for CMR-FT-derived strain (Fig. 8). The MVP patients showed less negative strain values in the basal segments except for the anterior septal segment compared to the controls, while the strain was more negative in the apical segments except for the inferior segment. However, in contrast to the CMR-FT findings, we did not observe a clear difference between the septal and the remaining myocardial segments.

Since our analysis software for CMR-FT and for STE divides the apical segments differently (4 segments + apex segment vs. 6 segments without apex segment), we did not examine the S6/S16 ratio.

Discussion

Summary

Our study identified differences in regional contraction patterns between MVP patients and controls without apparent heart disease. To date, it is the CMR study with the largest study

Table 3 Standard CMR parameters and global strain values of controls and patients with MVP

Standard CMR parameters	Controls (<i>n</i> = 50)	Patients with MVP (<i>n</i> = 132)	Controls (<i>n</i> = 50)	Patients with MVP (<i>n</i> = 132)
	Mean $\pm$ SD	Mean $\pm$ SD	Adjusted marginal mean (95% CI)	Adjusted marginal mean (95% CI)
LVEDVi (ml/m ²)	71.8 $\pm$ 10.7	82.9 $\pm$ 17.3	68.8 (64.5 to 73.1)	84.6 (82.0 to 87.2)
LVESVi (ml/m ²)	27.4 $\pm$ 6.0	32.7 $\pm$ 9.3	25.4 (23.1 to 27.6)	33.7 (32.4 to 35.1)
LVSVi (ml/m ²)	44.6 $\pm$ 7.0	50.1 $\pm$ 10.1	43.8 (41.1 to 46.5)	50.7 (49.1 to 52.3)
LVEF (%)	61.6 $\pm$ 5.4	60.3 $\pm$ 5.5	62.8 (61.3 to 64.3)	59.8 (58.9 to 60.7)
LA area (cm ²)	19.9 $\pm$ 4.6	20.4 $\pm$ 7.4	19.7 (18.5 to 20.8)	19.4 (18.4 to 20.5)
LV basal septal thickness (mm)	8.7 $\pm$ 1.6	9.9 $\pm$ 1.9	8.7 (8.3 to 9.2)	9.9 (9.7 to 10.2)
LV basal lateral thickness (mm)	6.9 $\pm$ 1.2	6.8 $\pm$ 1.3	6.8 (6.5 to 7.1)	6.9 (6.7 to 7.1)
LV GLS (%)	−21.8 $\pm$ 2.6	−21.6 $\pm$ 3.8	−22.0 (−23.0 to −21.0)	−21.5 (−22.1 to −20.9)
LV GCS (%)	−30.1 $\pm$ 3.9	−30.5 $\pm$ 5.7	−30.7 (−32.2 to −29.3)	−30.3 (−31.2 to −29.4)
RV free wall LS (%)	−32.6 $\pm$ 5.4	−34.0 $\pm$ 7.0	−33.3 (−35.2 to −31.4)	−33.6 (−34.7 to −35.4)
LA reservoir strain (%)	38.2 $\pm$ 10.8	33.8 $\pm$ 18.9	35.6 (32.7 to 38.5)	31.8 (29.5 to 34.2)

Unadjusted data as mean $\pm$ standard deviation (SD), adjusted data as estimated marginal means along with 95% confidence interval (CI), adjusted for age and sex differences using multivariable linear regression with group, age, and sex as covariates

MVP mitral valve prolapse, *LVEDVi* left ventricular end-diastolic volume index, *LVESVi* left ventricular end-systolic volume index, *LVSVi* left ventricular stroke volume index, *LVEF* left ventricular ejection fraction, *LA* left atrial, *LV* left ventricular, *GLS* global longitudinal strain, *GCS* global circumferential strain, *RV* right ventricular, *LS* longitudinal strain

Table 4 Native basal septal T1 values of controls and patients with MVP

	Field strength	Controls		Patients with MVP (<i>n</i> = 132)	
		<i>n</i>	T1 value (ms)	<i>n</i>	T1 value (ms)
Unadjusted mean	1.5 T	12	984 $\pm$ 31	32	1016 $\pm$ 34
	3 T	14	1230 $\pm$ 34	34	1247 $\pm$ 50
Adjusted mean	-	26	1110 (1094 to 1125)	66	1130 (1120 to 1140)

Unadjusted data as mean $\pm$ standard deviation (SD), adjusted data as estimated marginal means along with 95% confidence interval (CI), adjusted for field strength, age, and sex differences using multivariable linear regression with group, field strength, age, and sex as covariates. Reference values are 903–1085 ms for 1.5 T and 1098–1354 ms for 3 T. T1 mapping was not performed in all patients and controls

MVP mitral valve prolapse

population investigating this topic. We found worse regional endocardial longitudinal strain values in the basal segments and better values in the apical segments in patients with MVP. Septal strain values appeared to be less affected than those of the other regions. In addition, we observed lower strain values in the medial anterior and anterolateral segments. We also noted a lower strain value ratio between the basal anterolateral and apical lateral segments in MVP patients. While global LV strain and RV free wall strain did not differ significantly between groups, LA reservoir strain was reduced in MVP patients.

Interpretation and comparison to other studies

Previous studies have suggested that the basal myocardial segments are particularly affected in MVP, although the

findings are conflicting on whether the strain is better or worse in patients with MVP [13, 14, 18–20]. Our results, showing reduced regional longitudinal strain in the basal anterior, lateral, and inferior segments, align with previous studies that reported impaired strain in these regions [13, 14, 19, 20].

The aim of this study was to quantify the influence of MVP-related mechanical alterations on CMR FT-derived strain measurements, especially in the basal segments. The abnormal mechanical conditions in these regions, particularly systolic curling and MAD, were therefore expected to affect strain assessment. Consequently, reduced strain values in the basal segments may reflect a combination of true contractile impairment and measurement effects related to CMR-FT under these mechanical conditions. The present findings help quantify this combined effect in

Table 5 CMR-FT-derived segmental longitudinal strain values (%) of controls and patients with MVP

Segment	Controls (<i>n</i> = 50)	Patients with MVP (<i>n</i> = 132)	Controls (<i>n</i> = 50)	Patients with MVP (<i>n</i> = 132)
	Mean $\pm$ SD	Mean $\pm$ SD	Adjusted marginal mean (95% CI)	Adjusted marginal mean (95% CI)
Basal anterior (S1)	-20.8 $\pm$ 5.2	-17.6 $\pm$ 8.0	-20.8 (-22.9 to -18.6)	-17.5 (-18.8 to -16.2)
Basal anteroseptal (S2)	-15.1 $\pm$ 6.7	-12.6 $\pm$ 8.0	-13.7 (-15.6 to -11.7)	-13.0 (-14.1 to -11.8)
Basal inferoseptal (S3)	-21.8 $\pm$ 5.6	-19.4 $\pm$ 7.5	-21.1 (-23.0 to -19.2)	-19.5 (-20.7 to -18.4)
Basal inferior (S4)	-29.3 $\pm$ 6.4	-26.2 $\pm$ 8.8	-29.5 (-31.8 to -27.1)	-26.0 (-27.4 to -24.5)
Basal inferolateral (S5)	-33.0 $\pm$ 8.3	-29.4 $\pm$ 11.8	-33.0 (-36.2 to -29.8)	-29.5 (-31.5 to -27.6)
Basal anterolateral (S6)	-32.7 $\pm$ 7.2	-27.7 $\pm$ 8.8	-33.4 (-35.9 to -31.0)	-27.4 (-28.9 to -25.9)
Medial anterior (S7)	-31.4 $\pm$ 7.2	-27.6 $\pm$ 7.9	-31.5 (-33.7 to -29.2)	-27.4 (-28.8 to -26.1)
Medial anteroseptal (S8)	-24.7 $\pm$ 6.8	-25.2 $\pm$ 8.1	-25.1 (-27.4 to -22.8)	-25.0 (-26.4 to -23.6)
Medial inferoseptal (S9)	-23.0 $\pm$ 6.3	-23.3 $\pm$ 7.4	-23.5 (-25.6 to -21.4)	-23.0 (-24.3 to -21.8)
Medial inferior (S10)	-26.4 $\pm$ 7.0	-28.7 $\pm$ 9.3	-26.9 (-29.4 to -24.4)	-28.3 (-29.8 to -26.8)
Medial inferolateral (S11)	-31.4 $\pm$ 9.6	-34.3 $\pm$ 10.7	-32.7 (-35.7 to -29.7)	-33.7 (-35.5 to -31.8)
Medial anterolateral (S12)	-31.8 $\pm$ 9.0	-30.8 $\pm$ 10.3	-33.9 (-36.6 to -31.1)	-29.8 (-31.4 to -28.1)
Apical anterior (S13)	-18.2 $\pm$ 9.4	-23.1 $\pm$ 10.6	-18.3 (-21.3 to -15.4)	-23.3 (-25.0 to -21.5)
Apical septal (S14)	-20.1 $\pm$ 6.0	-23.1 $\pm$ 6.7	-20.5 (-22.4 to -18.7)	-23.0 (-24.1 to -21.9)
Apical inferior (S15)	-20.0 $\pm$ 6.8	-25.7 $\pm$ 9.7	-20.2 (-22.8 to -17.5)	-25.6 (-27.2 to -24.0)
Apical lateral (S16)	-18.7 $\pm$ 6.7	-22.8 $\pm$ 9.3	-18.8 (-21.4 to -16.3)	-22.7 (-24.2 to -21.1)
Apex (S17)	-28.1 $\pm$ 6.4	-31.1 $\pm$ 7.0	-28.9 (-30.8 to -26.9)	-30.8 (-32.0 to -29.6)

Unadjusted data as mean $\pm$ standard deviation (SD), adjusted data as estimated marginal means along with 95% confidence interval (CI), adjusted for age and sex differences using separate multivariable linear regressions with group, age, and sex as covariates for each strain segment
CMR cardiac magnetic resonance, *FT* feature tracking, *MVP* mitral valve prolapse, *S* segment

an otherwise healthy MVP cohort and can support clinicians in interpreting regional strain abnormalities in MVP patients by facilitating the differentiation of mechanical measurement effects from true myocardial dysfunction.

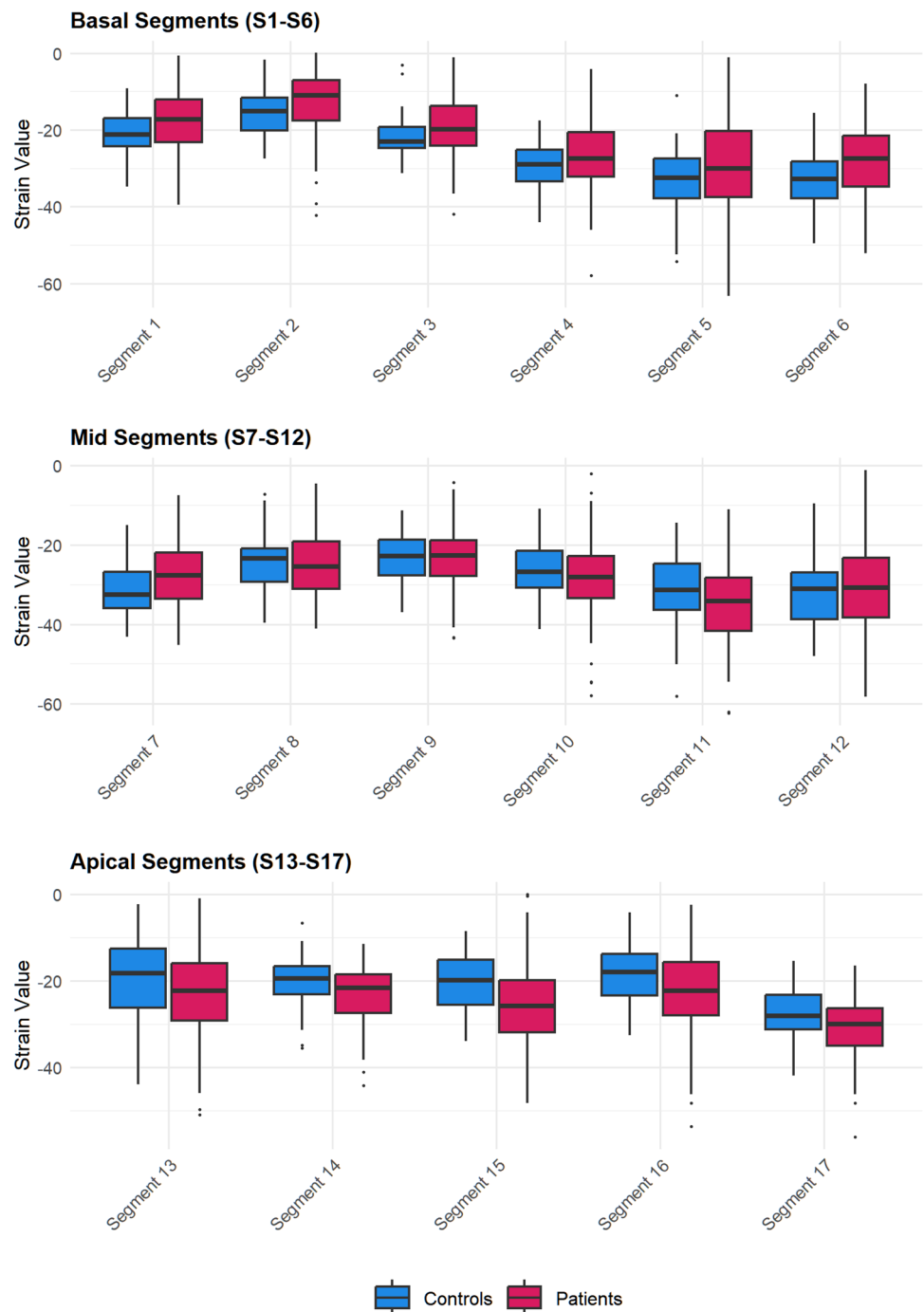
Previous studies showed that local myocardial fibrosis is often detected in the basal segments near the mitral annulus [36, 37], suggesting that reduced strain values may indeed at least partially reflect impaired myocardial contraction. This is further supported by our findings, as MVP patients with local fibrosis showed a predominant distribution in the basal and medial inferior and inferolateral segments [36, 37], corresponding to the regions with reduced strain in our cohort. Myocardial fibrosis is of clinical importance due to its association with ventricular arrhythmias [20]. Abnormal mechanical stress due to the prolapsing leaflets could trigger remodeling processes and the development of fibrosis, especially in the basal annular region. It was also observed that fibrosis in the basal segments is often associated with abnormal mechanics like a curling motion of the basal valve-linked structures [14]. In our study, approximately 17% of the MVP patients who underwent contrast-enhanced imaging showed signs of myocardial fibrosis, which is similar to the results other studies have reported (~25%) [36, 38]. The combination of impaired

longitudinal strain and the presence of abnormal mechanics could be assessed for its value to detect patients with high-risk MVP in future studies.

It is worth noting that the MVP patients in our cohort generally showed only mild displacement of the mitral valve. Since almost no other study on MVP and strain reported the mean prolapse distance of their patient population, we can only speculate whether this parameter would influence the strain measurement. Nagata et al. found that MVP patients with LV fibrosis had greater displacement of the leaflets. Their MVP patients had a similar mean prolapse distance to our patients. A larger prolapse distance could imply more mechanical stress for the myocardium adjacent to the mitral annular ring, potentially promoting fibrosis. In theory, this would be expected to worsen the strain in the basal segments. Further studies are needed to clarify this relationship and to determine whether greater leaflet displacement may also be associated with increased involvement of the medial and apical segments.

The relatively similar septal strain values for MVP patients and controls suggest that MVP may not severely affect the septal myocardium, which supports the hypothesis that mechanical stress due to leaflet prolapse predominantly affects regions adjacent to the mitral annulus, while septal regions remain functionally preserved.

Fig. 6 Boxplots of unadjusted regional longitudinal strain values (%) for controls and patients with mitral valve prolapse. Data presented as median with inter-quartile ranges. S segment



Similar to previous trials, we also did not see any relevant differences in LV global strain values, as the impaired strain values in the basal and part of the medial segments in MVP patients were compensated by better strain values in the apical segments. The lower strain value ratio between the basal anterolateral and the apical lateral segment in MVP patients also indicates a predominant apical deformation of the myocardium, at least for the lateral region. This observation has not been described before. Castillo-Sang et al. described a worse regional longitudinal strain in the apical lateral

segment and a worse average apical longitudinal strain in MVP patients compared to controls, but strain analysis was based on echocardiography and only patients with bileaflet prolapse and outward movement of the subannular base and posterior mitral annulus in late systole were examined [13]. Interestingly, previous studies reported that MVP patients with ventricular arrhythmia exhibited worse GLS compared to MVP patients without arrhythmia [39, 40]. Based on this finding, it might be hypothesized that risk for arrhythmia is increased in MVP patients without adequate compensation

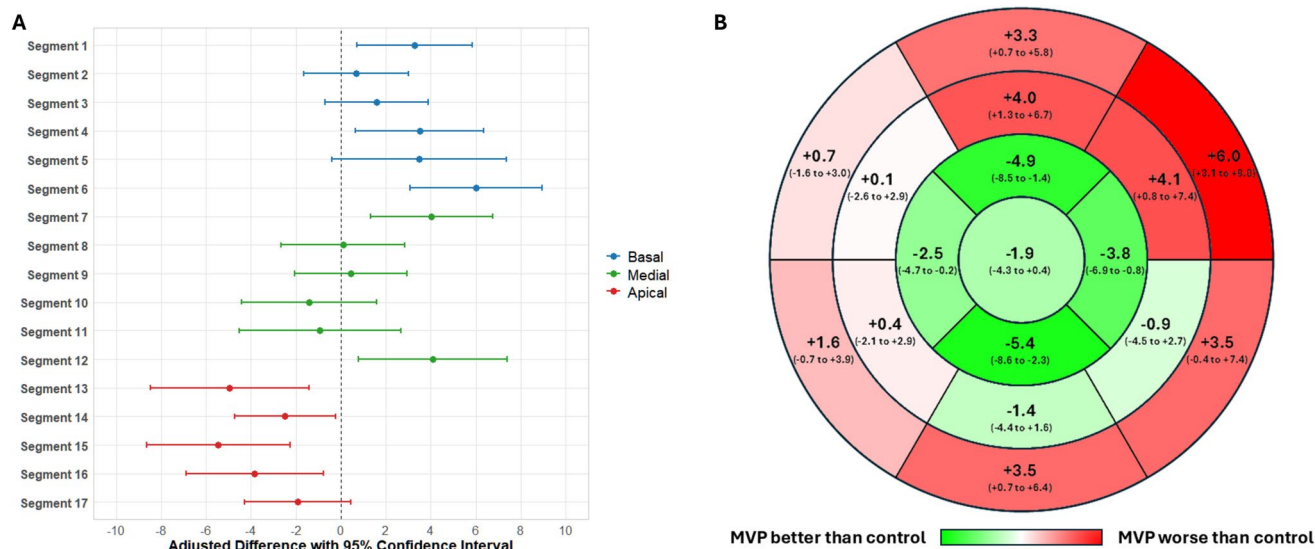


Fig. 7 Coefficient plot (A) and bullseye plot (B) of adjusted differences in percentage points in CMR-FT-derived mean regional longitudinal strain between patients with mitral valve prolapse and controls

Statistical analysis using multivariable linear regression for each strain segment separately, adjusting for age and sex. CMR cardiac magnetic resonance, FT feature tracking, MVP mitral valve prolapse

Table 6 Strain value ratio S6/S16 of controls and patients with MVP

Group	Geometric mean $\times/\div$ geometric SD	Adjusted marginal mean (95% CI)
Controls ($n=50$)	1.84 $\times/\div$ 1.68	1.84 (1.58 to 2.33)
Patients with MVP ($n=132$)	1.26 $\times/\div$ 1.90	1.32 (1.13 to 1.54)
- With MAD ($n=43$)	1.38 $\times/\div$ 1.79	1.45 (1.13 to 1.90)
- Without MAD ($n=89$)	1.20 $\times/\div$ 1.95	1.23 (1.02 to 1.48)
- With curling ($n=90$)	1.24 $\times/\div$ 1.88	1.29 (1.07 to 1.58)
- Without curling ($n=42$)	1.29 $\times/\div$ 1.97	1.28 (1.01 to 1.67)
- With LGE ^a ($n=19$)	1.19 $\times/\div$ 1.68	1.26 (0.94 to 1.61)
- Without LGE ^a ($n=95$)	1.23 $\times/\div$ 1.98	1.24 (1.01 to 1.56)

Data as unadjusted geometric mean $\times/\div$ geometric standard deviation (SD) and adjusted estimated marginal means along with 95% confidence interval (CI), adjusted for age and sex, using a multivariable linear regression on log-transformed data with back-transformed results, for the strain value ratio S6/S16

MVP mitral valve prolapse, MAD mitral annular disjunction, LGE late gadolinium enhancement

^aOnly 114 of the 132 MVP patients underwent an examination with contrast agent

of the apical segments. This is particularly interesting in light of the observation that impaired GLS is also present in patients with early heart failure [41]. Further investigation is needed to examine the potential connection between ventricular arrhythmia in MVP patients and heart failure.

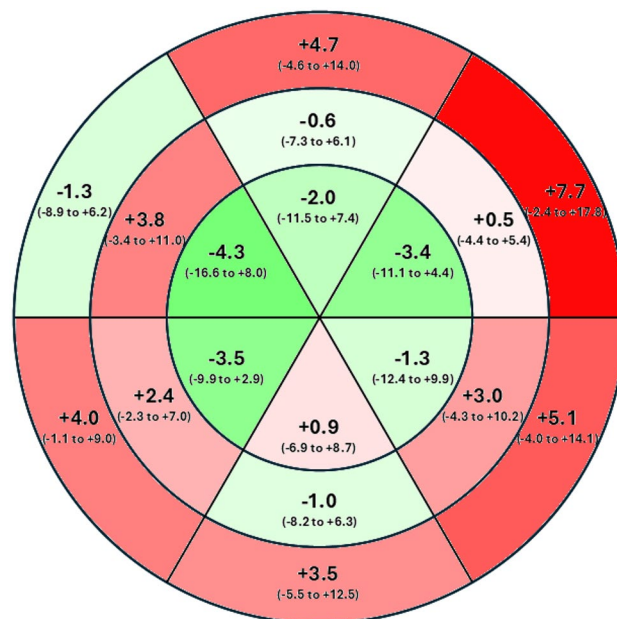


Fig. 8 Bullseye plot of adjusted differences in percentage points in TTE-STE-derived mean regional longitudinal strain between patients with mitral valve prolapse and controls. Statistical analysis using multivariable linear regression for each strain segment separately, adjusting for age and sex. MVP mitral valve prolapse, STE speckle tracking echocardiography

In a subgroup analysis, we observed that MVP patients with concomitant MAD exhibited a higher strain value ratio between the basal anterolateral and apical anterolateral

segments compared to MVP patients without MAD. Over the last decade, MAD has increasingly moved into the focus of research, as several studies have reported an association with an increased risk of ventricular arrhythmias [42, 43]. It has been hypothesized that MAD leads to altered mechanical load transmission to the myocardium, potentially mediated via the papillary muscles, resulting in abnormal myocardial mechanics [44]. Our findings could be interpreted as indicating that in MVP patients with MAD, the compensatory increase in apical deformation observed in MVP patients without MAD is less pronounced. A reduced apical compensation for impaired basal contraction may therefore represent a potential mechanistic link between MAD and the increased arrhythmic risk described in previous studies. However, this interpretation is limited by the absence of a significant difference in the strain value ratio between MVP patients with and without LGE. This may in part be explained by the fact that not all patients underwent contrast-enhanced imaging, the overall number of patients with myocardial fibrosis was relatively small, and fibrotic lesions were not uniformly located within the lateral myocardial segments. Consequently, further studies are required to better evaluate the relationship between MAD, regional strain patterns, myocardial fibrosis, and arrhythmic risk in MVP patients.

Since RV free wall strain was also similar in both groups, the LA reservoir strain remained the only strain parameter besides segmental strain where a relevant difference could be observed between MVP patients and controls. The fact that MVP patients showed a worse LA reservoir strain is remarkable, as we excluded patients with moderate or higher valvular insufficiency from the analysis. This indicator for a possible primary atrioopathy was also described by Tastet et al. who reported a reduced LA function in patients with bileaflet MVP and no or mild mitral regurgitation [45]. They hypothesized that this phenomenon could be caused by an increased mechanical stretch on the LA walls due to the abnormal motion of the leaflets which could lead to LA remodeling [45]. Another possibility is a deleterious effect of the prolapse volume, which is lost to circulation, akin to mitral regurgitation volume.

As mentioned in the introduction and in the methods, echocardiography-based speckle tracking and CMR-FT are based on fundamentally different technologies and methods of tissue tracking, each with its own strengths and limitations, which means that strain measurements are not interchangeable between those two modalities [21]. Therefore, to further assess the robustness of our CMR-FT findings, we compared them to STE-derived strain values in a subgroup of patients who underwent both examinations. Despite the considerably smaller sample size, the STE-derived regional strain pattern was similar to the CMR-FT findings, with worse strain in the basal segments and better strain in the apical segments in MVP patients compared to controls.

This could be interpreted as an indication that the observed regional strain pattern reflects a genuine mechanical phenomenon in MVP rather than a modality-specific effect of CMR-FT.

Within CMR-FT, the selection of the analysis tool may also impact the result of the strain analysis [16, 46]. For example, Romero Daza et al. used cvi42 by Circle Cardiovascular Imaging (Calgary, Alberta, Canada) [18], whereas we and Guglielmo et al. used QStrain by Medis [19, 20]. This could also be an influencing factor for the inconclusive findings of this study compared to previous studies.

Limitations

A limitation of this study is its retrospective design. Most MVP patients in our cohort underwent CMR not primarily due to the mitral valve prolapse itself but rather for other clinical indications such as symptoms like dyspnea and decreased functional capacity or suspected cardiomyopathy. Although no pathological findings were detected in the CMR scan, undetected conditions could still have caused the symptoms and influenced strain values. This potential bias means that our study population may not fully represent the typical phenotype of asymptomatic MVP cases. As this analysis was based on routine clinical CMR reports, detailed information on the original referral indications was not consistently available. Additionally, although we adjusted for age and sex, differences in baseline parameters could still bias the results.

The CMR images analyzed in this study were acquired on two scanners with different field strength and over a 10-year period during which scan parameters varied. This may introduce technical variability. However, previous studies suggest that these factors have only minimal to no effect on myocardial strain measurements [46, 47].

Another limitation of our study is that we used one of many commercially available programs to perform the CMR-FT. It is unclear if our results are reproducible on other platforms, since different software platforms use varying algorithms for contour detection, tracking, and strain computation. It is also noteworthy to mention that our assessment of LA reservoir strain could be affected by through-plane motion of the left atrium given the fact that the image planning of the cine sequences is based on the left ventricle and the CMR-FT relies on 2D images for analysis.

Conclusion

With this retrospective study, we identified altered regional longitudinal strain patterns in patients with MVP, with impaired strain in the basal segments and increased strain in the apical segments. Future studies with larger samples

are required to link this observation to clinical symptoms and outcomes like mitral valve insufficiency, ventricular arrhythmias, and sudden cardiac death and thereby help to improve risk stratification in MVP patients.

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Declarations

Conflict of interest SK received lecture honoraria from Medis, NL. PD received travel subsidies from Philips Healthcare. CS is an employee of Philips Healthcare.

Declaration of generative AI and AI-assisted technologies During the preparation of this work, the authors used ChatGPT and DeepSeek to assist in writing the R code for statistical analysis. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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