



Changes in strain parameters at different deterioration levels of left ventricular function: A cardiac magnetic resonance feature-tracking study of patients with left ventricular noncompaction

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ARTICLE INFO

Article history:

Received 14 July 2020

Received in revised form 25 November 2020

Accepted 28 January 2021

Available online 9 February 2021

Keywords:

Left ventricular noncompaction

Cardiac magnetic resonance

Feature-tracking

Strain

Heart failure

ABSTRACT

Background: There is a lack of cardiac MRI information on left ventricular (LV) strain and rotational parameters of left ventricular noncompaction (LVNC) patients with reduced ejection fraction (EF). Thus, we sought to use feature tracking (FT) to describe these changes at different levels of EF deterioration.

Methods: We included 31 adult LVNC patients with reduced LV EF (Group B, EF < 50%) without any comorbidities or concomitant cardiac diseases, 31 age- and sex-matched LVNC patients with good EF (Group A, EF > 50%) and 31 healthy controls. Group B was divided according to LV EF into two subgroups (Group B-1: EF 35–50%, Group B-2: EF < 35%). Their global longitudinal, circumferential (GCS), and radial (GRS) strains; LV segmental strains; LV apical and basal rotation values; and patterns and degree of LV dyssynchrony were measured.

Results: All of the global and mean segmental strain parameters were significantly worse in Groups B, B-1 and B-2 than in Group A and in the controls. The LV mechanical dispersion increased as LV EF decreased. The degree of apical rotation was the highest in the control group, almost the same in Group A and the lowest and in the reverse direction in Group B-2. A rotational pattern, clockwise-directed rigid body rotation (RBR), was found in 39% of the Group B patients, and a counterclockwise-directed RBR was found in 26% of the Group A patients.

Conclusions: The strain values and rotational parameters changed as the EF decreased. These changes affected the global LV, and we did not identify an LVNC-specific strain pattern.

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1. Introduction

Left ventricular noncompaction (LVNC) is a genetic disorder in which there is a higher than normal amount of trabeculated endocardial muscle in the left ventricular (LV) apex [1]. Cardiac magnetic resonance (CMR) is the recommended diagnostic modality, and several diagnostic criteria have been published based on the different ratios or values of the two distinct myocardial layers [2]. However, the presence of endocardial trabeculation is not limited to LVNC. Prominent trabeculation exceeding this diagnostic ratio can also be found in 27.5% of the healthy adult population without loss of left ventricular function over time [3]. However, patients with LVNC can develop congestive heart failure in

30% to 50% of cases, and it was found in 0.95–3.8% of explanted hearts after orthotopic heart transplantations [4–6].

A large number of speckle-tracking echocardiography studies were conducted with the aim of describing the myocardial deformation pattern of patients with LVNC and developing new and additional diagnostic criteria [7–9]. Nonetheless, the results are controversial. It has already been described that LV ejection fraction (EF) highly correlates with global longitudinal and circumferential strain [10]. Moreover, the changes in global strain values and segmental strain patterns have been studied in patients with nonischemic dilated cardiomyopathy (DCM) measured with both speckle-tracking echocardiography and CMR feature-tracking [11,12]. However, we did not find comprehensive information about the feature-tracking strain characteristics of LVNC patients with different levels of LV EF deterioration.

In this retrospective study, we aimed to describe the changes in LV global and regional strain parameters that occur in patients with noncompacted LV with good to significantly reduced EF and to compare their characteristics with those observed in healthy controls. Furthermore, we assessed disease-specific strain characteristics.

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2. Methods

Between October 2007 and June 2019, out of a total of 12,326 CMR examinations, 171 patients had excessive LV trabeculation and good LV function ($EF > 50\%$), and 180 were diagnosed with LVNC and a reduced EF ($EF < 50\%$). Petersen's and Jacquier's criteria were used for the diagnosis of LVNC [13,14]. In this retrospective study, 31 Caucasian LVNC patients with good LV function (Group A, $EF > 50\%$, age: 49.5 ± 10.9 years, male: 21) and 31 LVNC patients with a reduced LV EF (Group B, $EF < 50\%$, age: 54.4 ± 12.1 years, male: 21) were included according to the following criteria: no concomitant ischemic or congenital heart disease and no presence of other cardiomyopathies, [2] no significant comorbidities, and [3] the CMR short and long axis cine images were acquired before the injection of contrast agent and did not contain artifacts [15]. In addition to this patient population, we included 31 age- and sex-matched healthy control subjects (age: 48.8 ± 9.6 years, male: 21) who did not have any cardiovascular or other systemic diseases and did not have excessive endocardial trabeculation in the apical part of the LV according to the applied criteria. We divided Group B by EF into two subgroups: Group B-1 contained the LVNC patients with an LV EF between 35 and 50% ($n = 13$, age: 51.5 ± 13.0 years, male: 8), and Group B-2 contained the patients with an EF lower than 35% ($n = 18$, age: 56.6 ± 11.3 years, male: 13). All procedures performed in this study were in accordance with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Ethical approval was obtained from the Central Ethics Committee of Hungary, and all participants provided informed consent. Table 1 shows the baseline characteristics of the studied groups.

The CMR examinations were performed on a 1.5-T MR scanner (Achieva, Philips Medical System, Eindhoven, the Netherlands) with a 5-channel cardiac coil. Retrospectively gated, balanced steady-state free precession cine images were acquired in 2-, 3-, and 4-chamber long-axis views, and breath-hold short-axis cine images were taken from base to apex.

The short-axis scans were used for the threshold-based image analysis. Semiautomatic tracking with manual correction of the endo- and epicardial borders was performed by two observers (A. Sz., who has 9 years of experience, and A. R. K., who has 3 years of experience) with the use of Medis Suite postprocessing software (Medis Suite, version 3.0, Medis Medical Imaging Systems, Leiden, the Netherlands). The LV parameters were calculated by a threshold-based papillary and trabeculated muscle quantification analysis software module (MassK module of Medis Suite). This software identifies endocardial trabeculae from the blood pool based on their differing signal intensities; thus, each voxel is classified as blood or myocardium according to the chosen signal intensity threshold, which was set at the default value (50%) [16]. We measured the end-diastolic volume (EDV), the end-systolic volume (ESV), the stroke volume (SV), the EF, the LV end-diastolic muscle mass (LV-Mass) and the LV end-diastolic papillary and trabeculated muscle mass (LV-Trab). The parameters were indexed (i) to body surface area. We used the normal values reported by Alfakih et al. [17].

The feature-tracking strain analysis was performed using commercially available software (QStrain, Medis Suite). The endocardial contours of 2-, 3-, and 4-chamber long- and short-axis cine images were manually traced. We measured the global strain parameters of the LV in the longitudinal (GLS), radial (GRS), and circumferential (GCS) directions (Fig. 1). To eliminate the possible inaccuracies of the feature-tracking segmental strain measurement, we calculated the mean segmental strain values of the apical, mid and basal thirds of the LV in both longitudinal and circumferential directions according to the 17- and 16-segment models [18]. To determine the degree of intraventricular synchronous contraction, the standard deviation of the time-to-peak strains between segments was analyzed in the longitudinal and circumferential directions (longitudinal mechanical dispersion: SD-TTP-LS; circumferential mechanical dispersion: SD-TTP-CS). Finally, the systolic peak rotation of the apical and basal parts of the LV was calculated, and the rotation pattern was analyzed. The normal rotation

Table 1
Left ventricular functional, global strain, mechanical dispersion and rotational values of the studied groups.

	p value	Group A vs. Control		Group B vs. Control		Group B-1 vs. Group A		Group B-2 vs. Group A		Group B-2 vs. Group B-1	
		Group A	Control	Group B	Group B-1	Group B-2	Group B-1	Group B-2	Group B-1	Group B-2	Group B-1
Number of participants (male)		31 (21)	31 (21)	31 (21)	13 (8)	18 (13)					
EDVi (ml/m ²)		66.4 ± 12.6	72.0 ± 12.5	121.8 ± 38.5	92.9 ± 13.0	142.6 ± 37.5					
ESVi (ml/m ²)		19.5 ± 4.9	25.4 ± 6.7	84.4 ± 36.1	53.0 ± 9.1	107.1 ± 30.8					
SVi (ml/m ²)		46.8 ± 8.8	46.6 ± 7.6	37.3 ± 9.1	39.9 ± 5.7	35.5 ± 10.7					
EF (%)		70.6 ± 4.2	65.0 ± 5.1	32.8 ± 10.1	43.1 ± 4.1	25.3 ± 5.3					
LV-Mass (g/m ²)		71.7 ± 13.8	80.9 ± 18.9	123.2 ± 29.4	98.5 ± 19.0	141.0 ± 21.6					
LV-Trab (g/m ²)		20.0 ± 4.1	28.4 ± 8.4	48.2 ± 13.2	38.9 ± 9.3	55.0 ± 11.5					
GLS (%)		−22.9 ± 2.5	−21.7 ± 2.5	−10.4 ± 3.9	−13.9 ± 2.6	−8.0 ± 2.6					
GRS (%)		62.3 ± 9.2	55.2 ± 8.2	20.2 ± 8.0	28.2 ± 4.0	14.5 ± 4.1					
GCS (%)		−35.0 ± 4.2	−31.0 ± 4.9	−11.0 ± 6.2	−7.3 ± 5.0	−2.2 ± 5.7					
Apical rotation (°)		10.1 ± 12.6	10.1 ± 8.7	0.1 ± 5.7	3.4 ± 5.4	−3.1 ± 3.9					
Basal rotation (°)		0.4 ± 8.8	−0.1 ± 6.5	−3.5 ± 4.2	−4.6 ± 4.3	−3.1 ± 3.9					
SD-TTP-LS (%)		12.2 ± 4.1	10.9 ± 4.4	15.9 ± 4.5	14.0 ± 4.4	17.2 ± 4.1					
SD-TTP-CS (%)		6.9 ± 3.4	7.6 ± 4.6	15.8 ± 5.3	13.9 ± 5.8	17.2 ± 4.5					
EDVi: end-diastolic volume index, EF: ejection fraction, ESVi: end-systolic volume index, GCS: global circumferential strain, GLS: global longitudinal strain, GRS: global radial strain, LV-Mass: end-diastolic myocardial mass index, LVNC: left ventricular noncompaction, LV-Trab: end-diastolic papillary and trabecular mass index, SD-TTP-LS: standard deviation of time-to-peak circumferential strains, SD-TTP-CS: standard deviation of time-to-peak longitudinal strains, SVi: stroke volume index.											

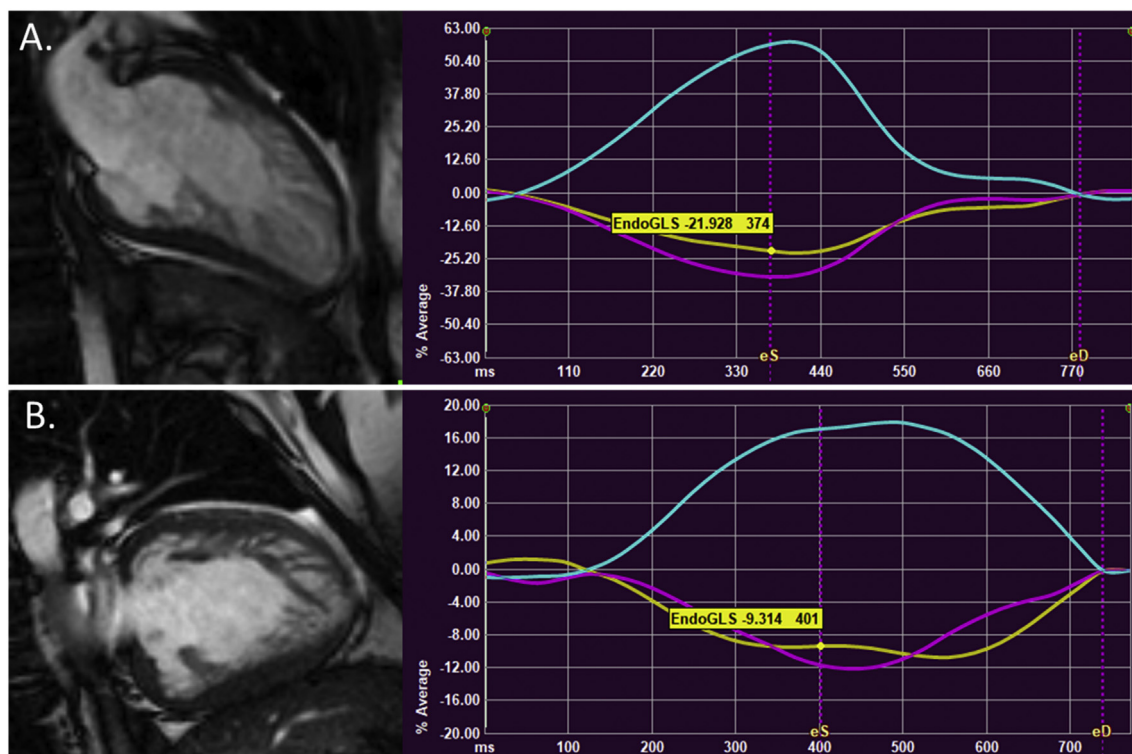


Fig. 1. Representative two-chamber long axis CMR images and the corresponding global strain curves of left ventricular noncompaction patients from Group-A with good ejection fraction (A), and from Group-B with decreased ejection fraction (B). The blue curve represents the global radial strain, the yellow curve represents the global longitudinal strain and the pink curve represents the global circumferential strain through the cardiac cycle. CMR: cardiac magnetic resonance, ED: end-diastole, ES: end-systole, GLS: global longitudinal strain.

pattern is characterized by a clockwise rotation at the base of the LV (negative value) and a counterclockwise rotation at the apical part of the LV (positive value). By rigid body rotation (RBR), we mean that the apical and basal parts of the LV rotated predominantly in the same direction [9]. The interobserver agreement of the two observers was tested regarding the threshold-based software module, the CMR feature-tracking and Petersen's criterion in ten randomly selected patients and ten controls.

Continuous variables are presented as the mean and standard deviation. Categorical variables are expressed as counts and percentages. The interobserver agreement was tested with and presented as the interclass correlation coefficient (ICC) and 95% confidence interval. The Shapiro-Wilk test was used to assess normal distributions. Levene's test was used to assess the equality of variances of the tested groups. Differences between the control and LVNC groups were analyzed with one-way analysis of variance (ANOVA) and Tukey's post hoc test in cases of normal distribution and equal variances, while the Welch test and Games-Howell post hoc test were used where the variances were unequal. Non-normally distributed data were analyzed with the Kruskal-Wallis test with Bonferroni correction for multiple comparison. A *p* value <0.05 was considered statistically significant. IBM SPSS Statistics (Version 25.0, Armonk, NY) was used for calculations. Figures were generated with GraphPad Prism version 8.0.0 for Windows (GraphPad Software, San Diego, California USA).

3. Results

The interobserver agreement of the measured functional parameters are as follows: EDV: 0.98 (0.95–0.99), ESV: 0.94 (0.84–0.98), SV: 0.90 (0.75–0.96), EF: 0.76 (0.40–0.91), LV-Trab: 0.95 (0.86–0.98), and LV-Mass: 0.99 (0.97–0.99). These results are interpreted as follows: less than 0.4 indicates poor, 0.4–0.75 indicates fair to good, and greater

than 0.75 indicates excellent. We also measured the interobserver agreement of the noncompacted-to-compacted ratio, which was 0.95 (0.83–0.99).

The interobserver agreement of the measured global strain parameters was also good to excellent: GLS: 0.96 (0.89–0.98), GRS: 0.99 (0.96–0.99), GCS: 0.96 (0.89–0.98), rotation: 0.68 (0.19–0.87), SD-TTP-LS: 0.87 (0.68–0.95), and SD-TTP-CS: 0.75 (0.38–0.90).

In the comparison of the LV functional parameters, we found that Group A had higher volumes, muscle and trabecular muscle mass values and a lower EF than the control group. Similar results were found when comparing Group B with Group A and controls. In Group B-1 and Group B-2, the volumes and muscle masses increased and the SV decreased with the decrease in the EF (Table 1). Late gadolinium enhancement with nonischemic midmyocardial pattern was present in 5 patients in Group B-1 and in 11 patients in Group B-2.

We compared the global strain parameters of Group B with those of Group A and controls. The GLS, GRS and GCS were significantly worse (i.e., the GLS and GCS were less negative and the GRS was less positive) in Group B than in Group A and in the controls, and the GCS and GRS were also significantly worse in the Group A than in the controls (Table 1).

After dividing Group B into two subgroups, we found that all the global strain parameters differed significantly among Groups A, B-1, and B-2. Specifically, the worse EF was associated with worse strain parameters (Table 1).

Fig. 2 shows the graphical representation of global strain values at different deterioration levels of LV EF.

A comparison of the mean longitudinal strain values of the apical, mid and basal parts of the LV among the groups showed that Group B had significantly worse longitudinal strain values in every part of the LV than Group A and the controls. These parameters did not differ between Group A and the controls. Comparisons of Group B-1 and

Global strains

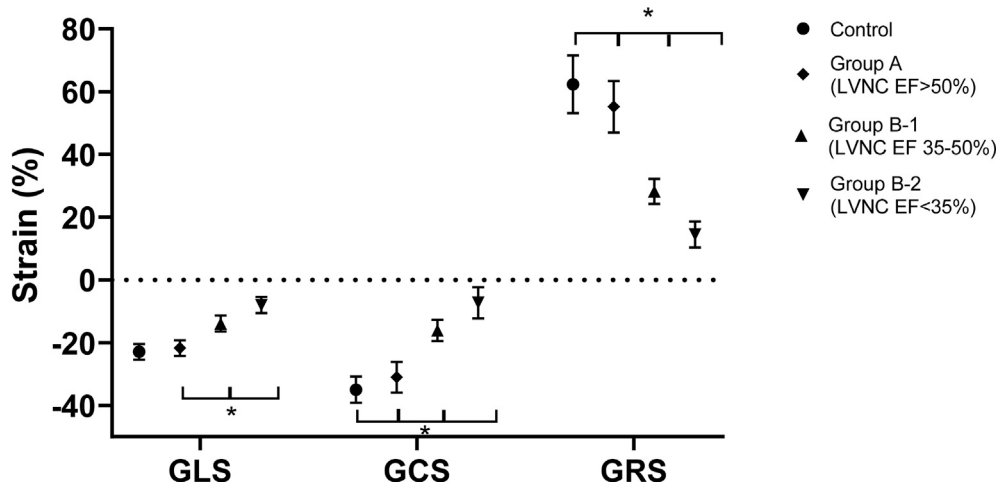


Fig. 2. Graphic representation of the global strain values at different level of left ventricular function. EF: ejection fraction, GCS: global circumferential strain, GLS: global longitudinal strain, GRS: global radial strain, LVNC: left ventricular noncompaction.

Group B-2 with each other and with Group A showed that the longitudinal strain values were significantly different among these groups in each part of the LV (Table 2).

Similar results were found when comparing the mean segmental circumferential strain values of the studied groups (Table 2).

In studying the mean apical, mid and basal LV longitudinal strain values in each group, we found that the LV mid part had the highest (i.e., more negative) strain value in every group. The basal part had the lowest (i.e., less negative) longitudinal strain values out of the three parts of the LV in Group A and in the controls, while the lowest values were found in the apical part of the LV in Groups B, B-1, and B-2 (Fig. 3a, Appendix).

Regarding the mean circumferential strains, we found significant differences among the apical, mid and basal LV strain values in Group A and the controls but not in Group B or its subgroups. The mean strain values were decreased in every part of the LV in Group B and its B-1 and

B-2 subgroups; however, the strain pattern remained the same, opposing the mean longitudinal strains where the pattern changed with the decrease in EF (Fig. 3b, Appendix).

The mechanical dispersion in both the longitudinal (SD-TTP-LS) and circumferential (SD-TTP-CS) directions was significantly higher in Group B than in Group A and in the controls, and there was no significant difference between the latter two groups. Regarding the B-1 and B-2 subgroups, the mechanical dispersion increased in both directions as EF decreased (Table 1).

The degree of peak apical rotation was almost equal between Group A and the controls, and it significantly decreased as the EF decreased. Notably, the direction of apical rotation was reversed in Group B-2. The basal rotation was significantly different between Group A and Group B; however, after dividing Group B, we found that the difference was significant only between Group B-1 and Group B-2 (Table 1).

Table 2

Comparison of the mean apical, mid and basal left ventricular longitudinal and circumferential strain values.

Longitudinal strain (%)				p value		
	Control	Group A LVNC EF > 50%	Group B LVNC EF < 50%	Group A vs. Control	Group B vs. Control	Group B vs. Group A
Apical	-23.3 ± 4.4	-22.5 ± 5.7	-11.4 ± 4.1	0.764	<0.0001*	<0.0001*
Mid	-24.9 ± 4.9	-24.0 ± 4.5	-14.2 ± 4.1	0.712	<0.0001*	<0.0001*
Basal	-22.3 ± 3.3	-21.2 ± 4.4	-13.6 ± 4.4	0.570	<0.0001*	<0.0001*
Circumferential strain (%)						
Apical	-41.4 ± 6.7	-34.3 ± 10.4	-15.2 ± 5.6	0.007*	<0.0001*	<0.0001*
Mid	-28.6 ± 4.4	-25.1 ± 3.6	-13.0 ± 3.9	0.002*	<0.0001*	<0.0001*
Basal	-34.4 ± 3.2	-31.1 ± 4.5	-15.1 ± 4.7	0.143	<0.0001*	<0.0001*
Longitudinal strain (%)				p value		
	Group A LVNC EF > 50%	Group B-1 LVNC EF 35–50%	Group B-2 LVNC EF < 35%	Group B-1 vs. Group A	Group B-2 vs. Group A	Group B-2 vs. Group B-1
Apical	-22.5 ± 5.7	-14.2 ± 4.1	-9.3 ± 2.8	<0.0001*	<0.0001*	0.015*
Mid	-24.0 ± 4.5	-17.3 ± 3.7	-11.9 ± 2.8	<0.0001*	<0.0001*	0.001*
Basal	-21.2 ± 4.4	-16.2 ± 3.8	-11.7 ± 4.0	0.002*	<0.0001*	0.012*
Circumferential strain (%)						
Apical	-34.3 ± 10.4	-19.3 ± 5.3	-12.3 ± 3.8	<0.0001*	<0.0001*	0.002*
Mid	-25.1 ± 3.6	-16.7 ± 2.6	-10.4 ± 2.0	0.001*	<0.0001*	0.043*
Basal	-31.1 ± 4.5	-19.1 ± 4.2	-12.2 ± 2.4	0.001*	<0.0001*	0.056

EF: ejection fraction, LVNC: left ventricular noncompaction.

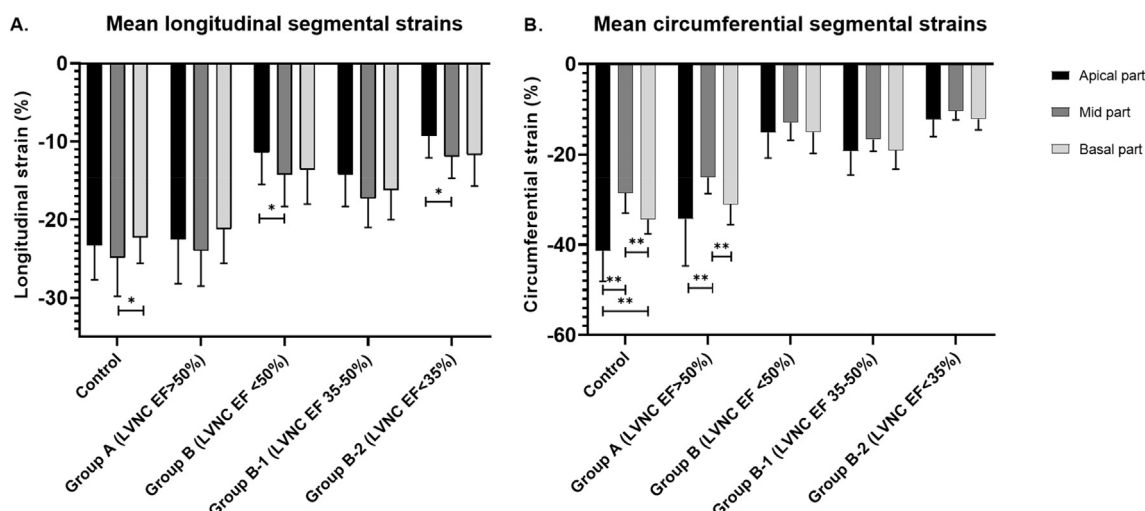


Fig. 3. Comparison of the mean apical, mid and basal left ventricular longitudinal (A) and circumferential (B) strain values in each group. Data and significance are presented in the Appendix. EF: ejection fraction, LVNC: left ventricular noncompaction, * $p < 0.05$, ** $p < 0.0001$.

Finally, in studying the LV rotational patterns of the LVNC and control groups, we found that RBR occurred in 42% of the patients in Group B (group B-2: $n = 10$, Group B-1: $n = 3$), in whom it was clockwise-directed in the majority of cases (Group B-2: $n = 10$, Group B-1: $n = 2$). Twenty-six percent of the patients in Group A also had RBR ($n = 8$); however, almost all of these patients showed counterclockwise RBR ($n = 7$). Surprisingly, 23% ($n = 7$) of the control subjects also had a counterclockwise-directed RBR.

4. Discussion

In this study, we described the LV global and segmental CMR feature-tracking strain characteristics of LVNC patients on the spectrum of a good to a severely reduced LV EF which may add to the comprehensive picture. The LVNC patients with reduced LV function had a remodeled LV with higher volumes, higher myocardial and trabecular mass and lower SV than LVNC patients with good LV function. These alterations correlate with previous studies describing the echocardiography and CMR features of LVNC patients with impaired systolic function, while an increased trabeculated muscle mass is characteristic of the disease [19,20]. The functional parameters of LVNC patients with a good LV EF compared with the healthy control participants were in the normal range, but the volumes and masses were higher, while the EF was lower. These findings are in accordance with previous studies and may be related to the presence of excessive endocardial trabeculation [21,22]. The clinical relevance of these volumetric and functional alterations is still unknown, and they should be evaluated together with the patient's symptoms, ECG findings, and medical history [23].

The LV is composed of a complex three-layered myocardial structure leading to the longitudinal, circumferential and radial-directed deformation of the myocardium [24]. It is already known that the LV global strains strongly correlate with the EF; thus, the worsening of LV function is associated with decreased LV global strain parameters [10,25,26]. In our study, we found that the GLS, GCS and GRS gradually decreased as LV function worsened. The decreased strains in all three directions suggest that LVNC is a complex structural disease that affects not only the noncompacted but the compacted layer as well [27,28].

Regarding the LVNC patients with good LV function, their GLS was not different from that of the control group, which is in accordance with the results of Gastl et al. [29]. However, this may be controversial, as other researchers found impaired GLS in both adult and pediatric LVNC patient populations despite having good LV function [22,30]. These conflicting results could be due to the non-linear relationship

between LV ejection fraction and GLS, namely, there is a stronger correlation between these two parameters at lower EF, and the curve flattens when the EF is higher than 50%. Thus, in this latter case, GLS can vary more with less effect on LV EF [25,26].

GCS and GRS were significantly worse in patients with a good LV EF compared with controls but were still in the normal range. Other researchers found similar results in pediatric patients and lower than normal GCS values in adult LVNC patients with good LV function as well [29,31]. However, decreased GCS and GRS values were also present in healthy participants with LV hypertrabeculation, and Cai et al. described that higher global fractal dimension values were independently associated with decreased GCS after adjusting for age, sex and body mass index [32,33]. This result raises the question of whether the presence of LV hypertrabeculation causes this alteration or subclinical LV dysfunction is already present in LVNC patients regardless of having good LV function. Follow-up studies with a large number of included LVNC patients should target this question, as neither the pathomechanism nor its clinical relevance has been determined.

In studying the mean segmental strain values of the apical, mid and basal regions, we found an increase in segmental strain values from base to apex, which has been previously described in healthy adults; however, our results were slightly different, namely, the mid part had the best longitudinal strain value, which may be due to the small number of included patients [34]. Previous CMR and speckle-tracking echocardiography studies have mentioned that these regional strain differences disappear in patients with DCM, and in accordance with this, we also observed that the decrease in segmental strains affected all three parts of the LV in LVNC patients with a reduced EF [27,35]. Furthermore, an opposite pattern was exhibited in this LVNC patient group; namely, the apical longitudinal strain became the worst of the three parts, which was previously described in different DCM and LVNC populations with a severely reduced EF [11,12]. Niemann et al. compared LVNC patients with a reduced EF to DCM patients with speckle-tracking echocardiography and found decreased apical strains in both groups; moreover, Tufekcioglu also found similar contraction properties between patients with LVNC and DCM [7,36]. These results together with the evenly decreased circumferential segmental strain values suggest that the regional strain patterns in LVNC are very similar to those described in DCM and not specific to noncompaction as an etiological factor of heart failure. However, opposing results regarding the apical strain in LVNC can be found in the literature, which might be due to the different strain measurement techniques and the different vendors [8]. Furthermore, the lack of an LVNC-specific pattern might be due to the small

sample size in our study, and the existence of LVNC-specific signs and patterns cannot be excluded. Further studies with a greater number of included patients are necessary.

Regarding the LVNC group with good LV function, significant differences were present only in the mean segmental circumferential strains, while the longitudinal values were not significantly different compared with those in the controls. These results are in accordance with the global strain results, namely, the decreased GCS and not differing GLS values. Thus, the underlying cause may be similar.

In addition to the advantages of feature-tracking, such as the postprocessing nature and the excellent reproducibility and correlation of global strains with both the gold-standard tagging and fast-strain encoded MRI methods (fast-SENC), we need to mention some disadvantages that might play a role in the inability to describe any LVNC-specific strain pattern [37,38]. The intraobserver and interstudy agreement for segmental strains seem to be the worst in feature-tracking when compared with tagging and fast-SENC; furthermore, the reproducibility is highly dependent on the observer's experience [37,39,40]. This might have affected our regional strain results; however, we tried to decrease it by taking the average values of the LV thirds.

Mechanical dispersion (SD-TTP-CS and SD-TTP-LS) increased in both the longitudinal and circumferential directions as EF decreased, a pattern characteristic of DCM according to echocardiographic studies; however, this parameter, when measured with CMR, had a smaller background [41,42].

The apical rotation value was significantly smaller in the patients with a reduced EF than in the patients with a good EF or the controls, and after dividing the patients by the EF, apical rotation decreased as LV function worsened. Furthermore, the direction of apical rotation was reversed in patients with severely decreased LV function (Group B-2). Kim et al. demonstrated using speckle-tracking echocardiography to show that the LV EF is correlated with the degree of apical rotation but not with the degree of basal rotation. Moreover, Popescu et al. suggested that a decrease in apical rotation is related to LV dilation and increased sphericity and reflects a more advanced disease stage, in accordance with our findings [43,44]. The lack of difference between the patients with good EF and healthy controls also strengthens this phenomenon. We found only a few significant results regarding basal rotation, perhaps because of the heterogeneous basal rotation values and the small number of included patients. Additionally, the importance of basal rotation is less well studied than the role of apical rotation in the LV EF, as described above.

LV rigid body rotation is mentioned in previous papers as a characteristic rotation pattern in LVNC; however, it has also been demonstrated in several other disorders, e.g., dilated and hypertensive cardiomyopathy, amyloidosis or different types of congenital heart diseases [9,45–47]. In our study population, a mainly clockwise-directed RBR was found in the patients with reduced EF. Some studies have shown that patients with a clockwise RBR have higher volumes and more severely reduced EF and LV remodeling, which leads to a decrease in apical rotation and can eventually result in reversed apical rotation and clockwise RBR [43,45,48,49]. These findings are in accordance with our own results. Interestingly, a counterclockwise RBR was more characteristic of the LVNC patients with a good EF, and it was present in almost a quarter of the control patients as well. This type of RBR was found to be a normal pattern in healthy infants, but the cause and importance of this alteration in healthy adults and LVNC patients with good LV function remains unclear [50]. We would like to highlight that RBR has mostly been studied with speckle-tracking echocardiography; thus, further research on the role and reproducibility of CMR strain measurement software is needed.

5. Conclusion

The strain values and rotational parameters gradually worsened as EF decreased in patients with LVNC. In this study, we could not identify

a pattern specific to LVNC; however, we cannot exclude its existence. For this reason, further prospective studies are needed with larger numbers of patients.

6. Limitations

This was a single-center study with a relatively small number of included patients. We needed to exclude individuals who received contrast agents prior to short-axis cine imaging because both functional parameters and strain values are altered when measured on postcontrast short-axis cine images [15,51]. Unfortunately, detailed clinical information (ECG, symptoms, genetic test result) was not available for the included LVNC patients.

We would like to mention some limitations of the feature-tracking method as well. This method lacks a relevant validation process; thus, its clinical application is questionable. The reproducibility of segmental strain is worse than that of the other acquisition-based techniques; thus, we need to be careful when evaluating LV regional dysfunction with feature-tracking. There is high variability in normal strain values between different vendors; thus, there is a lack of an accepted normal reference range (37, 40).

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors report no relationships that could be construed as a conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijcard.2021.01.072>.

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