Impact of Myocardial Fibrosis on Left Ventricular Function Evaluated by Feature-Tracking Myocardial Strain Cardiac Magnetic Resonance in Competitive Male Triathletes With Normal Ejection Fraction

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Background: To analyze the effect of myocardial fibrosis on left ventricular (LV) function evaluated by feature-tracking strain analysis by cine cardiac magnetic resonance (CMR) in competitive male triathletes with normal ejection fraction (EF).

Methods and Results: 78 asymptomatic male triathletes with >10 weekly training hours (43±11 years) and 28 male age-matched controls were studied by late gadolinium enhancement (LGE) and cine CMR. Global and segmental radial, longitudinal and circumferential strains were analyzed using feature-tracking cine CMR. Focal non-ischemic LGE was observed in 15 of 78 triathletes (19%, LGE+) with predominance in the basal inferolateral segments. LVEF was normal in LGE+ (62±6%) and LGE− triathletes (62±5%, P=0.958). In contrast, global radial strain was lower in LGE+ triathletes at 40±7% compared with LGE− triathletes (45±7%, P<0.05). Reduced segmental radial strain occurred either in LGE+ segments or in directly adjacent segments. Strain analysis revealed regional differences in controls, with the highest radial and longitudinal strain in the inferolateral segments, which were typically affected by fibrosis in LGE+ triathletes.

Conclusions: Reduced global and regional radial strain suggests a negative effect of myocardial fibrosis on LV function in LGE+ triathletes with normal EF. The observed regional differences in controls with the highest radial and longitudinal strain in the inferolateral segments may explain the typical occurrence of fibrosis in this myocardial region in triathletes.

Key Words: Athletes; Cardiac magnetic resonance imaging; Contrast media; Fibrosis; Myocardium

Myocardial fibrosis detected by late gadolinium enhancement (LGE) cardiac magnetic resonance (CMR) occurs in a variable number of athletes, with studies reporting a prevalence between 0% and 50%.1-7 The pattern of myocardial fibrosis in athletes suggests either an ischemic or non-ischemic genesis and several causes of non-ischemic fibrosis are currently discussed, including silent myocarditis, pulmonary artery pressure overload and repetitive myocardial microdamage.8 A recent work reported a series of 83 triathletes with myocardial fibrosis detected in 17% of the male triathletes on LGE CMR, but in none of the female triathletes.9 Non-ischemic LGE was observed in this study with predominant involvement of the inferolateral myocardium of the left ventricle (LV). In Anderson-Fabry disease it is suggested that increased wall stress and impaired resistance to physical stress are potential explanations for the typical inferolateral LGE involvement in such patients.10 However, the reasons for the noticeable involvement of this region in male triathletes remain to be elucidated.

Myocardial strain analysis using feature-tracking enables the analysis of global and segmental myocardial systolic contraction using standard cine CMR images.11 It has shown that myocardial strain detects impaired systolic
function in symptomatic patients with preserved ejection fraction (EF), and that myocardial strain is superior to EF for predicting survival in patients with ischemic or non-ischemic cardiomyopathy. We hypothesized that global and segmental myocardial strain would detect myocardial contraction anomalies in triathletes with myocardial fibrosis (LGE+) compared with triathletes without myocardial fibrosis (LGE−).

The purpose of the study was to analyze the effect of myocardial fibrosis on LV function evaluated by feature-tracking myocardial strain by cine CMR in competitive male triathletes with normal EF.

**Methods**

**Triathletes and Controls**

The institutional ethics committee approved the study and all subjects gave written informed consent. The authors had full control of the data and the material submitted for publication. Male triathletes were contacted through advertisement at local triathlon clubs. Inclusion criteria were weekly training ≥10 h and regular participation in triathlon competitions of various distances in the past 3 years. Triathletes reported their regular training hours per week and the number of active training years. A total of 79 competitive male triathletes (age: 43 ± 11 years, range 18–66) and 28 male control subjects with a similar age distribution (40 ± 10 years) were enrolled between April 2014 and December 2017 (Figure 1A). Control subjects were eligible if they exercised <3 h/week. Study exclusion criteria were contraindications for CMR or any systemic diseases. One male triathlete with known arterial hypertension was excluded from the study. None of the 78 triathletes and controls had any history of cardiovascular disease and reported no intake of any cardiac or illicit medications. All subjects underwent the CMR study before the exercise test, which was performed on the same day. All subjects were instructed to arrive rested without exercising or drinking alcohol in the preceding 72 h. Food and caffeine intake was restricted in the preceding 3 h. Blood samples were drawn immediately before the CMR from an antecubital vein while resting supine for 5 min to obtain hematocrit, creatine kinase, high-sensitivity troponin T (hs-TnT), and N-terminal pro-B-type natriuretic peptide (NT-proBNP).

**CMR Protocol**

CMR was performed using a 1.5-T Achieva scanner equipped with a 5-channel cardiac phased array receive coil (Philips Healthcare, Best, The Netherlands). The CMR protocol included standard steady-state free-precession cine CMR in the short axis for the LV and right ventricle (RV) volumetry and LV mass, and 3 long-axis cine CMR images in standard 2-, 3- and 4-chamber views with the following typical imaging parameters: acquired voxel size (AVS) 1.98 × 1.80 × 6 mm³, reconstructed voxel size (RVS) 1.36 × 1.36 × 6 mm³, gap 4 mm, 9–10 slices for full LV coverage, echo time = 1.67 ms, time to repetition = 3.34 ms, flip angle = 60°, parallel acquisition technique = SENSE factor 2.0, 25 phases per RR interval. Ten minutes after bolus injection of 0.2 mmol/kg gadoter acid (Dotarem®, Guerbet, Sulzbach, Germany) at a rate of 2.5 mL/s end-diastolic LGE images were acquired using end-diastolic phase-sensitive inversion recovery sequences in short-axis orientation covering the entire heart and in two-, three- and four-chamber views with the following typical imaging parameters: AVS 1.59 × 1.71 × 8 mm³, RVS 0.97 × 0.98 × 8 mm³, gap 2 mm, 9–10 short-axis slices, echo time = 2.40 ms, time to repetition = 5.50 ms, flip angle = 15°. The optimal inversion delay was obtained from a Look-Locker experiment.

**LV Function on Cine CMR and LGE Quantification on Contrast-Enhanced CMR**

Two investigators independently and blindly analyzed all CMR images and the data are given as the mean of the 2 observers. CMR parameters were indexed to the calculated body surface area (BSA). LV volume, mass and LGE size were evaluated using cvi42 software (Circle Cardiovascular Imaging Inc, Calgary, Alberta, Canada) in standard fashion on the short-axis cine images. Myocardial fibrosis was quantified using a threshold method with a cutoff >5 standard deviations (SD) above remote normal myocardium. The extent of global and segmental fibrosis was evaluated and reported as %LV and g/m² or % per segment, respectively. The distribution and pattern of LGE was visually analyzed and reported using the 16-segment model of the American Heart Association.

**Global and Segmental Strain Analysis**

Myocardial strain was analyzed on cine CMR images using segment feature-tracking software version 2.1.R.6108 (Medviso, Lund, Sweden) with known excellent interobserver reproducibility. This software analyzes myocardial strain by computing the interframe deformation fields using an endocardial tracking strategy based on non-rigid image registration. Instead of myocardial boundary tracking only, the software uses the entire image content (i.e., blood pool, entire myocardium) during the optimization process. Global and segmental longitudinal and radial strain were measured on 3 long-axis cine CMRs using standard 2-, 3- and 4-chamber views, whereas global and segmental circumferential strains were measured on 3 short-axis cine CMRs at the apical, middle and basal LV sections. Endo- and epicardial contours were manually delineated on end-diastolic images and were then automatically propagated by the software throughout the cardiac cycle generating myocardial strain values. Global and segmental strain were measured in controls and triathletes. For correlation between segmental strain and segmental LGE size the individual strains were normalized to the strain of the controls, because of the observed regional differences in myocardial strain, using the following formula: (individual segmental strain of a triathlete-mean segmental strain of controls)/mean segmental strain of controls × 100.

**Exercise Test**

A ramp-incremental cardiopulmonary exercise test was performed on an eddy current brake cycle ergometer (Ergosleek 100, Ergoline GmbH, Bitz, Germany) to determine the maximal power and peak oxygen uptake (VO₂peak), which was calculated as the average of the 3 highest measurements within the final minute. The 12-lead ECG and heart rate were monitored continuously, and blood pressure was automatically measured every 2 min using an upper arm cuff. The ramp-incremental exercise test was preceded by a 2-min resting period, followed by cycling at a low workload (20 W for 3 min) until a steady state of gas exchange was attained. Depending on the individual’s training history, the load was continuously increased.
increased in constant steps by 20–40 W/min to bring the participant to the limit of tolerance within 10–12 min of exercise.

**Statistical Analysis**
Statistical analysis was performed using MedCalc for Windows, version 13.3.3.0 (MedCalc Software, Ostend, Belgium) and SAS for Windows, version 9.4 (SA Institute Inc., Cary, NC, USA). Continuous data are presented as mean±SD and categorical data are presented as absolute numbers and percentages. Bland-Altman analysis was used to determine agreement between the 2 investigators. The intraclass correlation coefficient was calculated to analyze the inter-rater reliability. Continuous data were compared

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Figure 1. (A) Subject flow chart. One triathlete was excluded because of arterial hypertension. (B) Short- and long-axis LGE images of a LGE+ triathlete and LGE− triathlete. The LGE+ triathlete had local non-ischemic mid-myocardial LGE, typically located in the basal inferior and inferolateral segments (B, Upper row). Feature-tracking myocardial strain analysis was performed on cine CMR images using dedicated software, which automatically propagated the endo- and epicardial contours throughout the cardiac cycle, generating global and segmental myocardial peak strain values (B, Lower row). The LGE+ triathlete had reduced global peak radial strain with 40% (C, Left), whereas the LGE− triathlete had normal global peak radial strain with 50% (C, Right). Segmental strain analysis showed reduced regional radial strain in the basal inferolateral LGE+ segments (D, Left, marked in red) and in the adjacent mid-inferolateral segments. CMR, cardiac magnetic resonance; LGE, late gadolinium enhancement.
blood pressure under exercise was higher in the triathletes compared with controls. V̇O₂peak and maximal power were higher in the triathletes compared with controls. CMR revealed larger LV mass indices as well as higher left and right ventricular volume indices in the triathletes compared with controls (Table 1).

Presence, Localization and Extent of Myocardial Fibrosis on Contrast-Enhanced CMR
CMR revealed non-ischemic LGE in 15 of the 78 (19%) male triathletes, but in none of the male controls (P<0.05). A LGE pattern typical of myocarditis was found in 13 triathletes, including 7 triathletes with subepicardial LGE location and a thin pericardial gap, while 6 triathletes had mid-myocardial LGE. Two athletes had LGE located at the posterior RV insertion point. LGE was typically located in the inferolateral segments (Figures 1B, 3D). The

| Table 1. Differences Between Male Triathletes and Controls |
|-------------|-------------|-------------|
|               | Male triathletes (n=78) | Male controls (n=28) | P value |
| Clinical parameters |             |             |         |
| Age, years      | 43±11       | 40±10       | 0.241   |
| Weight, kg      | 78±9        | 80±9        | 0.263   |
| Height, m       | 1.81±0.07   | 1.81±0.09   | 0.689   |
| BMI, kg/m²      | 23.7±2.3    | 24.5±2.2    | 0.072   |
| BSA, m²         | 1.98±0.13   | 2.00±0.15   | 0.527   |
| Exercise parameters |         |             |         |
| Systolic BP at rest, mmHg | 125±15     | 122±14      | 0.531   |
| Diastolic BP at rest, mmHg  | 83±10     | 85±11       | 0.511   |
| Peak systolic BP, mmHg     | 199±28     | 181±34      | <0.05   |
| Peak diastolic BP, mmHg    | 91±21      | 82±21       | 0.087   |
| HR at rest, beats/min     | 67±13      | 76±13       | <0.01   |
| Peak HR, beats/min        | 169±13     | 173±15      | 0.255   |
| ΔHR rest/peak, beats/min  | 103±16     | 99±17       | 0.287   |
| V̇O₂peak, mL/kg/min       | 54±9       | 59±6        | <0.0001 |
| Maximal power, W           | 407±108    | 242±43      | <0.0001 |
| Blood parameters           |             |             |         |
| Hematocrit, %             | 0.44±0.03   | 0.43±0.02   | 0.398   |
| hs-TNT, pg/mL             | 7±8        | 5±3         | 0.323   |
| NT-proBNP, pg/mL          | 41±60      | 34±23       | 0.579   |
| CMR parameters            |             |             |         |
| HR on CMR, beats/min      | 53±9       | 65±11       | <0.0001 |
| LVEF, %                   | 62±5       | 61±8        | 0.519   |
| Cardiac index, L/min/m²   | 3.3±0.7    | 3.4±0.9     | 0.717   |
| LV mass index, g/m²       | 82±12      | 66±9        | <0.0001 |
| LVEDVi, mL/m²             | 99±13      | 83±12       | <0.0001 |
| LVESVi, mL/m²             | 38±8       | 33±10       | <0.01   |
| LVSVi, mL/m²              | 61±8       | 50±8        | <0.0001 |
| RVEF, %                   | 57±7       | 59±7        | 0.174   |
| RVEDVi, mL/m²             | 102±16     | 85±14       | <0.0001 |
| RVESVi, mL/m²             | 44±11      | 35±10       | <0.0001 |
| RVSVi, mL/m²              | 58±11      | 50±8        | <0.001  |
| LGE present               | 15 (19%)   | 0 (0)       | <0.05   |

Numbers are mean ± SD for continuous and n (%) for categorical data. BMI, body mass index; BSA, body surface area; BP, blood pressure; HR, heart rate; hs-TNT, high-sensitivity troponin T; LGE, late gadolinium enhancement; LV, left ventricular; LVEF, left ventricular ejection fraction; LVEDVi, left ventricular end-diastolic volume index; LVESVi, left ventricular end-systolic volume index; LVSVi, left ventricular stroke volume index; NT-proBNP, N-terminal pro-B-type natriuretic peptide; RVEF, right ventricular ejection fraction; RVEDVi, right ventricular end-diastolic volume index; RVESVi, right ventricular end-systolic volume index; RVSVi, right ventricular stroke volume index; V̇O₂peak, peak oxygen uptake.

using two-sided Student t-tests and categorical variables were compared using Chi-squared test or Fisher’s exact test as appropriate. One-way ANOVA test was used to compare strain values among the controls, LGE+ and LGE− triathletes. If significant differences were detected, all pairs of groups were tested with one linear mixed model to control for cumulative type I error, which occurs with multiple testing. Statistical significance was defined as P<0.05.

**Results**

**Demographics and CMR Characteristics of Triathletes and Controls**
No differences were observed between male triathletes and male controls regarding age, weight, height, BMI and BSA (Table 1). Resting heart rate was lower and peak systolic blood pressure under exercise was higher in the triathletes compared with controls. V̇O₂peak and maximal power were higher in the triathletes compared with controls. CMR revealed larger LV mass indices as well as higher left and right ventricular volume indices in the triathletes compared with controls (Table 1).

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CMR revealed non-ischemic LGE in 15 of the 78 (19%) male triathletes, but in none of the male controls (P<0.05). A LGE pattern typical of myocarditis was found in 13 triathletes, including 7 triathletes with subepicardial LGE location and a thin pericardial gap, while 6 triathletes had mid-myocardial LGE. Two athletes had LGE located at the posterior RV insertion point. LGE was typically located in the inferolateral segments (Figures 1B, 3D). The
Impact of Myocardial Fibrosis on LV Function

The training history revealed no differences between the groups of triathletes. EF was identical in both groups of triathletes. LGE+ triathletes had higher LV mass index at 89±12 g/m² compared with LGE− triathletes at 81±12 g/m² (P<0.05).

Reproducibility of Myocardial Strain Measurement

Bland-Altman analysis revealed very good reproducibility of the longitudinal, radial and circumferential global and segmental strain measurements with high interobserver agreement and without systematic over- or underestimation, narrow absolute and relative limits of agreement and high intraclass correlation coefficients of 0.91–0.99 (Table 2). The training history revealed no differences between the groups of triathletes. EF was identical in both groups of triathletes. LGE+ triathletes had higher LV mass index at 89±12 g/m² compared with LGE− triathletes at 81±12 g/m² (P<0.05).

Demographic and CMR Characteristics of LGE+ and LGE− Triathletes

LGE+ triathletes showed a trend for a higher age (P=0.096) and weight (P=0.071) and had higher BMI (P<0.05) compared with LGE− triathletes (Table 2). Peak systolic blood pressure was higher in LGE+ triathletes, at 221±21 mmHg, compared with LGE− triathletes (193±27 mmHg, P<0.001). VO2peak and maximal power were similar for both groups, as were blood biomarkers of myocardial damage, including hs-TnT and NT-proBNP.

Table 2. Demographic and CMR Parameters in LGE+ and LGE− Male Triathletes

| Parameter                                      | LGE+ male triathletes (n=15) | LGE− male triathletes (n=63) | P value |
|------------------------------------------------|-----------------------------|-----------------------------|---------|
| Demographic parameters                         |                             |                             |         |
| Age, years                                     | 47±9                        | 42±11                       | 0.096   |
| Weight, kg                                     | 82±8                        | 77±8                        | 0.071   |
| Height, m                                      | 1.82±0.05                   | 1.82±0.07                   | 0.926   |
| BMI, kg/m²                                     | 24.7±2.5                    | 23.4±2.2                    | <0.05   |
| BSA, m²                                       | 2.03±0.11                   | 1.98±0.13                   | 0.188   |
| Exercise parameters                            |                             |                             |         |
| Systolic BP at rest, mmHg                      | 131±17                      | 123±14                      | 0.106   |
| Diastolic BP at rest, mmHg                     | 83±11                       | 83±10                       | 0.893   |
| Peak systolic BP, mmHg                         | 221±21                      | 193±27                      | <0.001  |
| Peak diastolic BP, mmHg                        | 89±12                       | 91±21                       | 0.728   |
| HR at rest, beats/min                          | 66±13                       | 67±13                       | 0.658   |
| Peak HR, beats/min                             | 165±11                      | 170±13                      | 0.242   |
| ΔHR rest/peak, beats/min                      | 100±14                      | 104±16                      |         |
| V̇O2peak, mL/kg per min                        | 53±8                        | 54±10                       | 0.741   |
| Maximal power, W                               | 375±79                      | 421±110                     | 0.146   |
| Blood parameters                               |                             |                             |         |
| Hematocrit, %                                  | 0.44±0.46                   | 0.44±0.25                   | 0.217   |
| hs-TNt, pg/mL                                  | 7±5                         | 7±9                         | 0.734   |
| NT-proBNP, pg/mL                               | 63±125                      | 35±29                       | 0.107   |
| Training history                               |                             |                             |         |
| Training hours per week                        | 11±3                        | 11±4                        | 0.933   |
| Active years, n                                | 15±7                        | 13±8                        | 0.329   |
| CMR parameters                                 |                             |                             |         |
| HR at CMR, beats/min                           | 53±9                        | 53±8                        | 0.931   |
| LVEF, %                                        | 62±6                        | 62±5                        | 0.958   |
| Cardiac index, L/min/m²                        | 3.3±0.6                     | 3.3±0.7                     | 0.860   |
| LV mass index, g/m²                            | 89±12                       | 81±12                       | <0.05   |
| LVEDVi, mL/m²                                  | 96±13                       | 100±13                      | 0.332   |
| LVESVi, mL/m²                                  | 36±7                        | 38±9                        | 0.492   |
| LVSVi, mL/m²                                   | 59±11                       | 62±7                        | 0.400   |
| RVEF, %                                        | 59±7                        | 57±6                        | 0.247   |
| RVEDVi, mL/m²                                  | 101±19                      | 103±16                      | 0.670   |
| RVESVi, mL/m²                                  | 41±10                       | 45±11                       | 0.230   |
| RVSVi, mL/m²                                   | 60±14                       | 58±9                        | 0.512   |
| Global LGE size, %LV                           | 2.9±2.3                     |                             |         |
| Global LGE mass, g/m²                          | 2.2±2.0                     |                             |         |
| Segmental LGE size, % per segment              | 13.6±13.1                   |                             |         |

Numbers are mean±SD for continuous and n(%) for categorical data. Abbreviations as in Table 1.
Segmental Strain in Controls

Segmental strain analysis showed regional differences in longitudinal and radial strain in the male controls (Figure 3). The most contraction with highest radial and longitudinal strain was observed in the controls in the basal inferolateral segments (e.g., segments 4 and 5), which were typically affected by fibrosis in LGE+ triathletes. For example, 80% of LGE+ triathletes had fibrosis in segment 5 and 60% of LGE+ triathletes had fibrosis in segment 4 (Figure 3D).

Figure 3. Segmental radial (A), longitudinal (B) and circumferential (C) strain analyses in controls revealed regional differences, with the highest radial and longitudinal strain in the inferolateral segments. (D) Frequency of segmental fibrosis in LGE+ triathletes. For example, 80% of LGE+ triathletes had fibrosis in segment 5 and 60% of LGE+ triathletes had fibrosis in segment 4. These 2 segments had the most radial and longitudinal strain in normal subjects. Segments with fibrosis are marked in red. LGE, late gadolinium enhancement.
Global and Segmental Myocardial Strain in LGE+ and LGE− Triathletes

Global radial strain was lower in LGE+ triathletes, with 40±7%, compared to LGE− triathletes (45±7%, P<0.05) and controls (45±8%, P<0.05, Table 3). Global longitudinal strain did not differ among the LGE+ and LGE− triathletes and controls. Global circumferential strain was similarly reduced in LGE+ compared with controls, indicating that this reduction represents a normal physiological adaption of the athlete’s heart rather than a pathological finding.

Correlation Between Segmental LGE Size and Segmental Strain

An inverse correlation was found between segmental LGE size and relative radial strain (P<0.01, Figure 5A), indicating the extent of myocardial fibrosis has a direct effect on myocardial contractility. No correlation was found between segmental LGE size and the relative longitudinal and circumferential strains (P=0.302 and P=0.840, respectively; Figure 5B,C).

Discussion

The current study analyzed systolic LV function using feature-tracking CMR strain analysis in competitive LGE+ and LGE− male triathletes and matching controls, providing insights into the potential mechanisms of myocardial fibrosis in athletes. First, we found regional differences in segmental myocardial strain in controls, with the highest strain in the inferolateral segments, which were typically affected by myocardial fibrosis in LGE+ triathletes. This finding suggests a hypothesis that increased contraction of the inferolateral myocardium could be an important co-factor in the development of myocardial fibrosis in competitive triathletes. Second, global and segmental radial strain was reduced in LGE+ compared with LGE− triathletes, but standard cine CMR revealed normal LV function in all triathletes, demonstrating the higher sensitivity of strain analysis for detecting abnormal systolic LV function. Third, an inverse correlation was found between LGE size and relative radial strain, revealing the direct effect of LGE size on myocardial function. Fourth, global circumferential strain was similarly reduced in LGE+ and LGE− triathletes compared with controls, indicating that this reduction represents a normal physiological adaption of the athlete’s heart rather than a pathological finding.

Regional Differences in Segmental Myocardial Strain in Controls

We found a distinct pattern of segmental longitudinal and radial strain in the controls, with the highest contraction in the basal inferolateral segments. A similar pattern was found by Tang et al, who analyzed segmental strain in healthy controls and in patients with ventricular arrhythmia without structural heart disease using feature-tracking CMR. The increased myocardial contraction of the inferolateral myocardial segments in our controls could be one explanation for the observed predominant occurrence of

Table 3. Global and Segmental Strain in Male Controls, LGE+ and LGE− Triathletes

| Strain, %          | Controls | LGE+    | LGE−    | P value | Controls | LGE+    | LGE−    | P value | Controls | LGE+    | LGE−    | P value |
|--------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Global strain      | 45±8    | 40±7†   | 45±7*   | 0.053   | -18±2   | -17±2   | -18±2   | 0.141   | -18±4   | -15±4†  | -14±3*  | <0.0001 |
| Basal segmental strain |
| 1 Anterior         | 33±10   | 33±13   | 33±13   | 0.999   | -15±7   | -15±5   | -16±5   | 0.645   | -21±8   | -18±6   | -18±5*  | 0.153   |
| 2 Anteroseptal     | 26±11   | 23±9    | 24±13   | 0.770   | -16±9   | -16±5   | -16±7   | 0.965   | -20±4   | -16±5   | -17±4*  | <0.05   |
| 3 Inferoseptal     | 17±8    | 18±6    | 17±9    | 0.976   | -26±7   | -21±6   | -25±6*  | <0.05   | -19±7   | -13±4   | -14±3*  | <0.01   |
| 4 Inferolateral    | 55±16   | 53±16   | 57±18   | 0.738   | -38±8   | -34±8   | -37±7*  | 0.161   | -12±4   | -9±4    | -9±4    | <0.01   |
| 5 Inferoseptal     | 65±19   | 47±17†  | 56±14** | <0.01   | -41±10  | -42±8   | -40±9   | 0.836   | -17±7   | -15±5   | -13±5*  | <0.05   |
| 6 Anterolateral    | 66±16   | 54±11†  | 62±13*  | <0.05   | -31±6   | -32±8   | -32±8   | 0.636   | -17±6   | -13±7   | -13±5*  | <0.01   |
| Middle segmental strain |
| 7 Anterior         | 46±14   | 43±15   | 52±15*  | 0.055   | -22±7   | -21±7   | -22±5   | 0.924   | -19±5   | -17±3   | -17±5*  | 0.095   |
| 8 Anteroseptal     | 28±11   | 29±11   | 31±12   | 0.621   | -17±5   | -15±7   | -16±5   | 0.568   | -19±5   | -16±5   | -18±4   | 0.105   |
| 9 Inferoseptal     | 35±8    | 33±7    | 34±8    | 0.833   | -11±5   | -11±6   | -10±6   | 0.644   | -20±7   | -17±4   | -15±4*  | <0.001  |
| 10 Inferolateral   | 46±12   | 41±9    | 44±11   | 0.420   | -14±5   | -12±4   | -11±5   | 0.050   | -14±5   | -11±5   | -9±3    | <0.0001 |
| 11 Inferoseptal    | 53±11   | 43±12†  | 50±11   | <0.05   | -16±7   | -14±6   | -14±6   | 0.380   | -16±5   | -13±4   | -13±5   | <0.05   |
| 12 Anterolateral   | 49±8    | 43±10   | 48±10   | 0.150   | -14±6   | -12±6   | -13±5   | 0.481   | -14±4   | -9±3    | -9±4    | <0.01   |
| Apical segmental strain |
| 13 Anterior        | 52±13   | 42±13†  | 50±12*  | <0.05   | -15±4   | -16±4   | -15±4   | 0.663   | -21±6   | -17±4   | -16±5*  | <0.01   |
| 14 Anteroseptal    | 39±13   | 32±11   | 38±13   | 0.151   | -17±5   | -17±4   | -18±5   | 0.382   | -25±7   | -21±8   | -19±5*  | <0.01   |
| 15 Inferoseptal    | 52±14   | 49±11   | 54±11   | 0.293   | -12±4   | -11±3   | -12±5   | 0.490   | -21±8   | -17±9   | -14±6*  | <0.001  |
| 16 Inferolateral   | 51±12   | 43±9‡   | 50±11   | 0.059   | -12±4   | -11±4   | -12±4   | 0.572   | -18±6   | -15±6   | -12±6*  | <0.01   |

*P<0.05 for LGE+ vs. LGE−; †P<0.05 or ‡P<0.01 or §P<0.001 for LGE+ vs. Controls; †P<0.05 or ¶P<0.01 or †P<0.001 for LGE− vs. Control. LGE, late gadolinium enhancement.
Reduced Strain in LGE+ Triathletes With Normal EF

We observed focal myocardial LGE in 19% of male competitive triathletes, which is in line with previous studies demonstrating an incidence of myocardial fibrosis in 0–50% of asymptomatic athletes. Our data showed reduced global radial and segmental strain in LGE+ triathletes with normal LV function on standard cine CMR, and pathologically increased blood pressure seem to be a likely explanation for the observed frequent LGE involvement of the inferolateral wall in triathletes.

Figure 4. Segmental strain analysis in LGE+ and LGE− triathletes. Radial strain was significantly lower in segments 5, 6, 7 and 13 in LGE+ triathletes compared with LGE− triathletes. Longitudinal strain was lower in segments 3 and 4, while circumferential strain was lower in segments 15 and 16 in LGE+ triathletes compared with LGE− triathletes. LGE, late gadolinium enhancement.

Figure 5. Correlation between segmental LGE size and segmental radial (A), longitudinal (B) and circumferential (C) strain. An inverse correlation was found between LGE size and relative radial strain (A, P<0.01), indicating that the extent of myocardial fibrosis has a direct effect on myocardial contractility. No correlation was found between LGE size and relative longitudinal and circumferential strain. LGE, late gadolinium enhancement.

non-ischemic fibrosis in this myocardial region. Our data may generate the hypothesis that increased contraction of the inferolateral myocardium could be an important cofactor in the development of myocardial fibrosis in competitive triathletes, who are exposed to a repetitive and sustained increase in myocardial wall stress during training and competition. LGE+ triathletes characteristically had higher systolic blood pressure under exercise and higher LV mass, resulting in an increased myocardial oxygen demand. The coincidence of physiologically increased contraction of the inferolateral wall, adaptive LV hypertrophy and pathologically increased blood pressure seem to be a likely explanation for the observed frequent LGE involvement of the inferolateral wall in triathletes.
revealing the higher sensitivity of strain analysis for detecting abnormal systolic LV function. A similar finding was observed by Kraigher-Krainer et al., who used strain analysis to study patients with symptoms of heart failure and preserved EF > 55%. That study showed a reduced global strain in those patients compared with both patients with hypertensive heart disease and controls. They concluded that abnormalities of LV systolic function measured by strain analysis may contribute to the syndrome of heart failure with preserved EF. Our study further highlighted the potential of strain analysis. EF was unable to reveal the consequences of subtle myocardial fibrosis in LGE+ triathletes, whereas radial strain analysis revealed reduced systolic LV contraction in these subjects. Therefore, strain analysis appears to be more suited to studying the effect of subtle myocardial fibrosis on systolic function.

Correlation Between Segmental LGE Size and Myocardial Strain

We observed an inverse correlation between segmental LGE size and segmental radial strain reduction, revealing the effect of LGE size on regional systolic LV function because radial strain represents myocardial wall thickening. No correlation was found between longitudinal or circumferential strain and LGE size, which is most likely related to the fact that these strains represent different components of myocardial contraction. Longitudinal strain reflects LV shortening from apex to basis, whereas circumferential strain represents myocardial fiber shortening along the circular perimeter. Our data showed that both components of myocardial contraction are less influenced by subtle LGE, because we did not observe differences in global longitudinal and circumferential strain between LGE+ and LGE− triathletes. A similar finding was reported by Maret et al., who compared radial and longitudinal strain by feature-tracking CMR with infarct size transmurality by LGE-CMR. That study showed an almost linear decline of radial strain in segments with increasing infarct size transmurality, but no such correlation was found for longitudinal strain.

In the present study, global circumferential strain was similarly reduced in the LGE+ and LGE− triathletes compared with controls, indicating that this reduction represents a normal physiological adaptation of the athlete’s heart rather than a pathological finding. This assumption is supported by the fact that our triathletes had larger LSVSi at lower heart rates compared with the controls, resulting in identical cardiac output. This adaptation reveals the capacity of the triathlete’s heart to produce normal cardiac output at lower circumferential strain. Our finding is supported by a recent study of Swoboda et al., who revealed reduced circumferential but similar longitudinal strain by tagging CMR in endurance athletes compared with controls.

Study Limitations

Because of the small sample size we could not analyze the relative contribution of the factors that potentially promote the occurrence of myocardial fibrosis in triathletes, such as increased blood pressure under exercise, increased myocardial mass and regional differences in myocardial contraction. Currently, no echocardiographic strain data are available to further support the current findings on reduced global or regional strain in LGE+ triathletes.

Conclusions

The observed normal regional differences in segmental myocardial strain with the highest contraction in the inferolateral segments may explain the typical myocardial fibrosis of this region in triathletes. Furthermore, radial strain analysis revealed reduced systolic function in LGE+ triathletes, revealing a negative effect of myocardial fibrosis on LV contraction in asymptomatic triathletes with normal EF. Follow-up studies are warranted to analyze the long-term effects of reduced strain on myocardial function measured by EF and on development of clinical symptoms of heart failure.

Disclosures

Dr. Stehning is an employee of Philips Healthcare, Hamburg, Germany. The other authors report no conflicts.

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**Supplementary Files**

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