Quantitative Evaluation of Myocardial Strain After Myocardial Infarction with Cardiovascular Magnetic Resonance Tissue-Tracking Imaging

Qian Zou, MD, Tian Zheng, MD, Shu-Li Zhou, MD, Xue-Pei Tang, MD, Shu-Hao Li, MD, Wei Zhou, MD and Liang-Geng Gong, MD

Summary

To investigate the value of cardiovascular magnetic resonance tissue-tracking (CMR-TT) imaging in the differentiation of subendocardial and transmural myocardial infarction (MI) and determine whether strain parameters are enable to detect adverse left ventricular (LV) remodeling.

Global peak circumferential, longitudinal, and radial strains (GPCS, GPLS, GPRS) and segmental peak circumferential, longitudinal, and radial strains (PCS, PLS, PRS) in accordance with the 16-segment model were all derived. All positive segments were divided into two groups according to transmural degree. All patients were dichotomized in accordance with the existence of LV remodeling, which was defined as infarct size (IS) > 24%.

Patients with MI showed significant lower GPRS, GPCS, and GPLS than the control group (16.41% ± 8.92%, −8.77% ± 3.51%, −7.54% ± 2.43% versus 32.41% ± 12.99%, −14.92% ± 3.32%, −11.50% ± 2.51%). Lower PRS [3.25% (−5.57, 7.835) versus 19.94% (12.50, 30.75), P < 0.001] and PCS (−3.81 ± 4.60% versus −8.97 ± 4.43%, P < 0.001) can be found in transmural infarcted segments compared to subendocardial infarcted segments. PLS between transmural and subendocardial infarcted segments (−4.03% ± 4.88% versus −4.34% ± 4.98%), without however statistical significance (P = 0.523). The optimal cutoff value for PRS in the discriminate diagnosis of MI was 8.97% with a sensitivity of 81.8% and specificity of 98.0%. The optimal cutoff value for PCS was −7.56% with a sensitivity of 83.6% and specificity of 72.1%. Receiver operating characteristic (ROC) analysis revealed an optimal cutoff GPRS of 15.45%, and GPCS of −6.72% yielded high diagnostic accuracy in the identification of remodeling, which was higher than left ventricular ejection fraction (LVEF).

CMR-TT can differentiate between subendocardial and transmural infarction and detect LV remodeling, and the diagnostic value was superior to conventional functional parameters.

Key words: Late gadolinium enhancement

To date, although cardiac death associated with myocardial infarction (MI) has been decreasing due to the improvement of medical techniques and patient management, it is still a major worldwide burden that accounts for the leading causes of death. A persistent long-term myocardial cell ischemia or death after MI is relevant to functional recovery or irreversible left ventricular (LV) remodeling.

Adverse LV remodeling is associated with poor outcome following MI. Despite percutaneous coronary intervention, LV remodeling occurs in 30%-35% of MI patients. Therefore, early prediction of adverse remodeling is clinically crucial for decision-making and may likely be targeted for therapeutic intervention.

Accurate identification of MI type or recognition of the transmural degree of infarction is an important factor for risk stratification because it has implication for both management and prognosis in patients with MI. Transmural MI was connected with poor outcome and increased incidence of major adverse cardiac events, while subendocardial infarcts are related to functional recovery after reperfusion therapy.

Although not suitable for patients with renal insufficiency owing to the contrast agent that can increase the risk of nephrogenic systemic fibrosis, late gadolinium enhancement (LGE) is an excellent in vivo standard for detecting MI and differentiating subendocardial infarction from transmural infarction. Moreover, LGE is inclined to overestimate the extent of MI by including edema in the peri-infarct zone.

From the 1Medical Imaging Center, The Second Affiliated Hospital of Nanchang University, Nanchang, PR. China and 2Medical Imaging Center, Shenzhen Hospital, Southern Medical University, Shenzhen, PR. China.

This work was supported by the Natural Science Foundation of China (grant number 81860316, 81660284).

Address for correspondence: Liang-Geng Gong, MD, Medical Imaging Center, The Second Affiliated Hospital of Nanchang University, No. 1 Min-de Road, Nanchang, Jiangxi 33000, PR. China. E-mail: gong111999@163.com

Received for publication July 23, 2019. Revised and accepted October 25, 2019.

Released in advance online on J-STAGE April 29, 2020.

doi: 10.1536/ihj.19-384

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Tissue-tracking (TT) was introduced as a novel technique for myocardial strain quantification that can be acquired from routine steady-state free precession (SSFP) cine sequences. Certain researches have indicated that TT can precisely calculate myocardial strain. The main purpose of this study was to investigate the value of TT in the differentiation of subendocardial and transmural MI and determine whether strain parameters are enable to detect the development of adverse LV remodeling compared to IS.

**Methods**

**Study population:** We retrospectively analyzed 45 patients with previous MI in The Second Affiliated Hospital of Nanchang University from June 2014 to December 2016. Among them, 6 cases were coincidentally found through physical examination, and the other 39 cases had definite diagnosis and treatment history of MI. Cardiovascular magnetic resonance (CMR) examination was performed 3 months to 2 years following the first presentation of MI. Moreover, 18 healthy volunteers as control group were enrolled in our study. All participants signed the informed consent, which was then approved by our hospital ethics committee.

All patients were included based on the diagnostic criteria of MI as follows: (1) patients with a definite clinical history of previous MI, (2) patients who showed evidences of MI on CMR or other imaging modalities, and (3) pathologic Q wave change identified on electrocardiogram, with or without symptoms. Patients in their first occurrence of AMI or with persistent ventricular arrhythmias or atrial fibrillation or accompanied with other types of cardiomyopathy were excluded. Further exclusion criteria were (1) contraindications to CMR including implantable pacemakers, defibrillators, or other metallic implants or (2) restriction to MR contrast agents.

**Imaging protocol:** CMR was performed on all subjects on a 3.0T GE scanner using 8-channel phased-array cardiac receive coil, with electrocardiogram triggering and respiratory gating technology. Cine imaging was acquired from SSFP sequence in both consecutive LV short-axis slices covering from the apex to the base and four-chamber long-axis views. LGE imaging was performed on inversion recovery gradient echo (IRFGR) sequence 8-10 minutes following a 0.2 mmol/kg intravenous dose of gadobenate dimeglumine (Gd-DTPA, Magnevist®, Bayer HealthCare Pharmaceuticals, Wayne, NJ, USA). Scan parameters are as follows: SSFP sequence, TR 3.8 ms, TE 1.6 ms, FOV 38 × 38 cm, matrix 256 × 256, flip angle 55°, slice thickness 7 mm, and slice space 0-1 mm, and IRFGR sequence, TR 6.8 ms, TE 3.2 ms, TI 170-250 ms, FOV 38 × 38 cm, matrix 256 × 256, flip angle 20°, slice thickness 7 mm, and slice space 2 mm.

**Imaging analysis:** Strain analysis and infarct size (IS) quantification were all obtained using Circle Cardiovascular Imaging Inc. (tissue-tracking, CVI 42 version 5.6, Calgary, Alberta, Canada). The epicardial and endocardial borders of the LV were manually delineated at end-diastole image and propagated. Global peak systolic circumferential, longitudinal, and radial strains (GPCS, GPLS, GPRS) and segmental peak systolic circumferential, longitudinal, and radial strains (PCS, PLS, PRS) in accordance with the American Heart Association’s 16-segment model were all derived excluding the apical cap, since the apex is not beneficial in observing the short-axis slice and the measurement error is relatively large. Patients will be delineated second times if the movement of contoured borders diverged from real myocardial motion badly and excluded from analysis if the epicardial or endocardial borders of the LV did not correctly delineated.

IS was expressed as the percentage of infarcted myocardial mass to LV total mass. Infarct area was defined as five or more standard deviations (SD) above that of the remote myocardium on LGE imaging. Cardiac functional parameters were also derived using commercial post-processing software (3D-short, CVI 42), including left ventricular ejection fraction (LVEF), end-diastolic volume (EDV), end-systolic volume (ESV), and stroke volume (SV).

All positive LGE segments were classified into two groups according to transmural extent of infarction: transmural extent ≤ 50% as subendocardial infarction and transmural extent > 50% as transmural infarction. All patients were dichotomized in accordance with the existence of LV remodeling, which was defined as IS > 24%.

**Statistical analysis:** The data were analyzed using SPSS version 23.0 (SPSS Inc. Chicago, IL, USA). The distribution normality of continuous variables was tested by one-sample Kolmogorov-Smirnov test. Continuous variables with normal distribution were presented as mean (SD), and non-normal variables were reported as median (inter-quartile range [IQR]). Means of two continuous normally distributed variables were compared by independent sample Student’s *t*-test. Other comparisons were performed using Mann-Whitney *U* test. Reproducibility of strain analysis was assessed using Intraclass Correlation Coefficient (ICC) for a subset of 27 randomly chosen cases, and Bland-Altman plots were constructed to demonstrate the agreement within interobserver. Receiver operating characteristics (ROC) curves, which were used to derive cut point to distinguish subendocardial MI from transmural MI and differentiate remodeling from non-remodeling group. Area under the curve (AUC), sensitivities, and specificities were respectively calculated. Correlation between parameters was assessed by Spearman’s rank coefficient. A value of *P* < 0.05 was considered significant (Figure 2).

**Results**

**Patient characteristics:** Forty-five patients (37 male, 8 female; median age (56 ± 12) years, range from 31 to 84 years) with previous MI and eighteen healthy controls were enrolled in the current study. Patient characteristics and LV function measured on CMR are summarized in Table I.

**MRI findings:** Myocardial strains and functional analysis PRS was expressed as median (IQR) because it is non-normally distributed. Patients with MI showed lower GPRS, GPCS,
Figure 1. A: A patient with primary inferior wall transmural infarction revealed on LGE imaging. B: Infarct zone marked with yellow area was defined as five or more SD above that of the remote myocardium on LGE imaging. C: Transmural extent of each segment corresponding to the American Heart Association’s 16-segment model was expressed as the percentage of segmental mass. D: A segmental map of peak radial strain. Peak longitudinal curves (E) and 16 segmental maps of peak longitudinal strain (F) of this patient.

Figure 2. Receiver operating characteristic (ROC) curves for distinguishing subendocardial MI from transmural MI based on strain parameters.

and GPLS than the control group (16.41% ± 8.92%, −8.77% ± 3.51%, −7.54% ± 2.43% versus 32.41% ± 12.99%, −14.92% ± 3.32%, −11.50% ± 2.51%), and there were significant statistical differences between them ($P < 0.001$). There were a total of 165 segments with transmural infarction and 129 segments with subendocardial infarction in this study, and lower PRS [3.25% (−5.57, 7.835)] versus 19.94% (12.50, 30.75), $P < 0.001$] and PCS (−3.81% ± 4.60% versus −8.97% ± 4.43%, $P < 0.001$) can be found in transmural infarcted segments compared to subendocardial infarcted segments. PLS between transmural and subendocardial infarcted segments (−4.03% ± 4.88% versus −4.34% ± 4.98%), without however reaching statistical significance ($P = 0.523$). A moderate positive correlation between GPRS and LVEF ($r = 0.56$, $P < 0.001$) and negative correlation between GPCS, GPLS,
and LVEF \((r = -0.654, P < 0.001, r = -0.682, P < 0.001,\) respectively) were found, while IS is not correlated with LVEF \((P = 0.268).\) The correlation of strain parameters and LV function indexes was revealed in Table II. Four patients were excluded in the IS assessment because part of LGE image quality was inadequate to outline endocardial contour. The remodeling group showed significant decreases among GPCS, GPRS, and GPLS as the non-remodeling group. For functional analysis, patients with remodeling had significantly lower LVEF as well as higher EDV and ESV than the non-remodeling patients, while the difference of SV between these two groups was not statistically significant (Table III).

ROC analysis ROC analysis was performed to assess the discriminatory power of strain parameters and conventional cardiac functional parameters in the diagnosis of MI. The optimal cutoff value for PRS in the discriminate diagnosis of MI was 8.97% with a sensitivity of 81.8% and specificity of 98.0%. The optimal cutoff value for PCS was \(-7.56\%\) with a sensitivity of 83.6% and specificity of 72.1%. The AUCs were 0.914 ± 0.017 and 0.827 ± 0.025, respectively. The diagnostic capability of global strain and cardiac function indexes for recognizing IS larger than 24% of total LV mass was revealed in Table III.

### Reproducibility:
Twenty-seven randomly chosen cases were reanalyzed for the interobserver reproducibility. GPCS, GPLS, and GPRS had excellent agreement between different observers (GPCS: ICC = 0.946, 95%CI: 0.882-0.975; GPLS: ICC = 0.957, 95%CI: 0.906-0.981; GPRS: ICC = 0.896, 95%CI: 0.771-0.952). The interobserver variability for PCS, PLS, and PRS (PCS: ICC = 0.872, 95%CI: 0.845-0.894; PLS: ICC = 0.796, 95%CI: 0.753-0.831; PRS: ICC = 0.788, 95%CI: 0.744-0.825) is relatively lower than global parameters, and the reproducibility of both GPRS and PRS is inferior than the circumferential and longitudinal strain. Bland-Altman plots were shown in Figure 3.

### Discussion
In this study, we valued the capacity of cardiovascular magnetic resonance tissue-tracking (CMR-TT) in the assessment of MI and detection of LV remodel. The main findings of this study were (1) that CMR-TT-derived strains have high reproducibility, (2) that myocardial strains can detect the extent of MI, (3) that there is a significant correlation between strain parameters and LVEF, and (4) that strain parameters could potentially recognized LV remodeling.

| Variables | Value |
|-----------|-------|
| Demographic data | |
| Age, years | 56 ± 12 |
| Male/female, n (%) | 37 (82%)/8 (18%) |
| Hypertension, n (%) | 18 (40%) |
| Hyperlipidemia, n (%) | 23 (51%) |
| Diabetes mellitus, n (%) | 6 (13%)/39 (87%) |
| Smoking, n (%) | 11 (24%) |

| LV function | |
| LVEF (%) | 50.15 ± 11.33 |
| EDV (mL) | 163.23 ± 60.84 |
| ESV (mL) | 105.18 ± 53.37 |
| SV (mL) | 62.7 ± 18.37 |

LVEF indicates left ventricular ejection fraction; EDV, end-diastolic volume; ESV, end-systolic volume; and SV, stroke volume.

| Variables | GPRS | GPCS | GPLS |
|-----------|------|------|------|
| \( r \) value | \( P \) value | \( r \) value | \( P \) value | \( r \) value | \( P \) value |
| LVEF | 0.56 | <0.001 | -0.654 | <0.001 | -0.682 | <0.001 |
| EDV | -0.404 | <0.01 | 0.491 | <0.01 | 0.437 | <0.01 |
| ESV | -0.53 | <0.001 | 0.596 | <0.001 | 0.597 | <0.001 |
| SV | 0.243 | 0.108 | -0.254 | 0.091 | -0.274 | 0.068 |

GPRS indicates global peak radial strain; GPCS, global peak circumferential strains; and GPLS, global peak longitudinal strain.

| Variables | Group 1 \((n = 17)\) | Group 2 \((n = 24)\) | \( P \) | Cutoff \((%\) | Sensitivity | Specificity | AUCs |
|-----------|------------------|------------------|-------|------------------|------------|------------|------|
| GPLS (%) | -6.02 ± 2.04 | -8.46 ± 2.33 | 0.001 | -7.16 | 0.77 | 0.75 | 0.77 |
| GPCS (%) | -6.42 ± 2.23 | -10.18 ± 3.16 | <0.001 | -6.72 | 0.65 | 0.92 | 0.84 |
| GPRS (%) | 10.73 ± 3.97 | 19.98 ± 8.67 | <0.001 | 15.45 | 0.88 | 0.75 | 0.84 |
| LVEF (%) | 45.8 ± 9.64 | 54.5 ± 10.71 | 0.011 | 51.50 | 0.71 | 0.67 | 0.74 |
| EDV (mL) | 185.22 ± 63.91 | 145.64 ± 53.17 | 0.028 | 204.98 | 0.45 | 0.88 | 0.702 |
| ESV (mL) | 127.11 ± 55.05 | 87.64 ± 45.86 | 0.012 | 64.50 | 0.95 | 0.56 | 0.724 |
| ESV (mL) | 58.09 ± 20.39 | 66.39 ± 16.05 | 0.134 | / | / | / | / |

Data expressed as mean ± standard deviation or \( n \). Group 1 patients with IS > 24%. Group 2 patients with IS ≤24%. AUC, area under the curve.
Identification of infarct types is of importance, because subendocardial infarcts are connected to better long-term outcomes and greater cardiac functional recovery after revascularization therapy. Our results showed that both PRS and PCS between transmural MI and subendocardial MI have a significant difference. However, PLS without reaching statistical difference between them. This may be a consequence of the three-dimensional helical arrangement of cardiac fibers. The myocardial fibers can be divided into three different anatomical directions: the innermost longitudinal oriented fibers, the middle circumferential wrapped fibers, and the outermost oblique ar-

Figure 3. Bland-Altman analysis for GPRS (A), GPCS (B), GPLS (C), PRS (D), PCS (E), and PLS (F) from interobserver.
rangement layers. MI is a pathological process that begins from the endocardium layer, which produced longitudinal strain. Given all this, subendocardial longitudinal myofi-
bers are most impressive and vulnerable to myocardial ischemia and are inclined to earlier injury, leading to markedly reduced longitudinal strain. These pathophys-
iological factors may explain why PLS was insignificant between subendocardial MI and transmural MI.

In our study, the preferable reproducibility was ac-
quired for circumferential and longitudinal strain, followed by radial strain. This is in accordance with the study con-
ducted by Taylor, et al. who also indicated that PRS had the lowest reproducibility. One possible reason is that PRS is achieved from both endocardial and epicardial direction movement, and as a result, its calculation depends on the accumulative tracking of two regions of interest. On this level, the comparison in signal at the epicardial boundary is less brilliant than that at the endocardial boundary, while it is totally different from the tracking of circumfer-
ential and longitudinal strain. Although the coefficient of segment parameters was inferior to the global, these still robustly estimate myocardial deformation.

Our results differ from the study by Kihlberg, et al. who reported that PCS showed best accuracy and highest sensitivity and specificity for detecting 50% transmurality with DENSE-derived strain, whereas our study demonstrated that PRS had relatively higher accuracy compared to PCS. This discrepancy may be partly due to the different measurement methods or the smaller population of our study.

Previous studies in the literature have focused on the value of LGE, myocardial function, and markers of myo-
cardial injury to predict LV remodeling at follow-up after acute MI. Only few studies verified the capability of global myocardial strain based on speckle-tracking echocardiography (STE) to predict adverse LV remodel-
ing, and results showed that GLS and GCS can be an excellent predictor of remodeling. However, our study dif-
fered from the previous research in the definition of re-
modeling. They defined LV remodeling as LV EDV >20% compared with baseline. Apart from that, we tracked myo-
cardial motion and deformation based on CMR-TT. Given the superiority of multiplane and higher-resolution imaging in soft tissues, CMR allows more precise estimation of myocardial structural and functional alternation after MI.

LGE has become the reference standard for assessing myocardial scar and focal fibrosis in both ischemic and nonischemic cardiomyopathy. LGE allows an excellent qualitative evaluation of myocardial necrosis after MI. However, the injection of contrast limits its widespread use, especially for patients with kidney disorders. Tissue-tracking-derived strain has been proven to have high reproducibility and therefore could be a reliable method in strain analysis as shown in previous study. Furthermore, CMR-TT without need for incremental sequence and con-
trast agent is a feasible option for patients with severe re-
nal impairment in whom gadolinium agents are contrain-
dicated. Another advantage of TT method is far shorter post-processing time than MR tagging and STE.

LV remodeling is a key prognostic factor in the proc-
ess of progressively developing from cardiac functional insufficiency to heart failure after AMI. Various factors led to remodeling, including anterior infarct location, patency of the criminal vessel, LVEF, IS, creatinine kinase, troponin T levels, and thrombolysis in MI (TIMI) flow. Our results exhibited that strain parameters have a moderate correlation with LVEF. By contrast, IS do not correlate with LVEF perhaps because LVEF reflects the total LV function; however, the dysfunction of infarcted zone is localized.

LGE precisely assessed IS following MI renders this technique as a useful method to discriminate patients at risk for remodeling. Several researches have emphasized the impact of IS on the progression of LV remodeling. Lund, et al. showed that an IS of 24% of LV area as a cutoff value predicted remodeling with high accuracy. The likelihood of remodeling progressively increased as the IS increased. Chareonthaitawee, et al. found a reduction in LVEF in the following years after AMI, which happened only in patients with an IS of more than 25%.

Based on the results of previous studies, our results prolonged the theory about the influence of IS on remodel-
ing. We divided patients into two groups according to the IS of 24%. Results showed that patients with IS >24% exhibited lower strain values compared to patients with IS ≤24%. ROC analysis revealed that an optimal cutoff GPRS of 15.45% and GPCS of −6.72% yielded high diagnostic accuracy in the identification of remodel-
ing, which was higher than the LVEF, EDV, and ESV. The cutoff value of GPLS was lower when compared with that estimate by Bochenek, et al. with STE. The main reason for the difference may rely upon the cohort characteristics: their population only included anterior MI, which is absolu-
tely related to wider myocardial necrosis. Nevertheless, Takeuchi, et al. did not find a significant difference in the aforementioned parameters in the discriminated LV remodel-
ing. Patients with remodeling require regular moni-
toring and intensively interfered with antiremodeling therapies to slow the development of LV expansion to heart failure. The results showed that global myocardial strain analysis after MI can recognize patients at increased risk of LV remodeling, without the need for contrast agent or exposure to ionizing radiation.

Myocardial strain is a novel parameter that precisely expresses inherent myocardial function than conventional parameters. CMR-TT, through manually delineated epicar-
dial and endocardial borders of the LV and propagated on cine imaging, automatically tracking the movement and direction of each pixel of myocardium and quantitatively measuring myocardial fiber deformation in all directions, achieved strain parameters that objectively reflect the LV function. Comparing with CMR tagging, the first applied technique for quantitative assessment of myocardial mo-
tion and deformation, CMR-TT, can identify remodeling and can therefore be a useful means for risk stratification of patients who experienced MI and shuns the difficulty of diastolic fading, without the need for additional image acquisitions. Furthermore, strain parameters showed comparatively lower interobserver variability. Owning to these advantages, myocardial strain as a supplementary tool of other modalities provided incremental value for prediction.
of poor outcomes after MI with brilliant prospects in clinical application.

Limitations: There are some limitations in our study. First, the number of patients included is relatively small, and large populations are needed to verify the findings. Second, our study was a cross-sectional investigation, not a longitudinal follow-up research, and while LV remodeling is a continuous process, it would therefore be important in the future to demonstrate that the findings can be replicated in a longitudinal study. Third, variable myocardial strain values were reported in different location of LV wall, while this factor was not considered according to the limitation of sample size.

Conclusions

Our study demonstrates that myocardial strain derived from CMR-TT is feasible for detecting the extent of MI and recognizing LV remodeling after MI. However, the prognostic value of the findings remains to be validated by further larger-scale longitudinal study.

Disclosure

Conflicts of interest: The authors declared no potential conflicts of interest with respect to the research and publication of this article.

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