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The Improvement of Torsion Assessed by Cardiovascular Magnetic Resonance Feature Tracking after Coronary Artery Bypass Grafting: A Sensitive Index of Cardiac Function

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ABSTRACT

Objective: The aim of this study was to quantify left ventricular torsion by newly applied cardiovascular magnetic resonance feature tracking (CMR-FT), and to evaluate the clinical value of the ventricular torsion as a sensitive indicator of cardiac function by comparison of preoperative and postoperative torsion.

Methods: A total of 54 volunteers and 36 patients with previous myocardial infarction (MI) and LV ejection fraction (EF) between 30%-50% were screened preoperatively or postoperatively by MRI. The patients' short axis views of the whole heart were acquired, and all patients had a scar area >75% in at least one of the anterior or inferior segments. Their apical and basal rotation values were analyzed by feature tracking, and the correlation analysis was performed for the improvement of LV torsion and ejection fraction after CABG. The intra- and inter-observer reliabilities of torsion measured by CMR-FT were assessed.

Results: In normal hearts, the apex rotated counterclockwise in the systolic period with the peak rotation as 10.2 ± 4.8°, and the base rotated clockwise as the peak value was 7.0 ± 3.3°. There was a timing hiatus between the apex and base untwisting, during which period the heart recoils and its suction sets the stage for the following rapid filling period. The postoperative torsion and rotation significantly improved compared with preoperative ones. However, the traditional indicator of cardiac function, ejection fraction, didn't show significant improvement.

Conclusion: Left ventricular torsion derived from CMR-FT, which does not require specialized CMR sequences, was sensitive to patients with low ejection fraction whose cardiac function significantly improved after CABG. The rapid acquisition of this measurement has potential for the assessment of cardiac function in clinical practice.

INTRODUCTION

Four hundred years ago, Richard Lower first observed the twisting motion of the left ventricle (LV) and depicted this movement as wringing out a wet towel [Lower 1968]. In the next 300 years, many researchers such as Torrent-Guasp [Torrent-Guasp 2001], Streeter [Streeter 1969], and Sengupta [Sengupta 2006] et al have devoted themselves to studying the structure of heart and LV torsion, and they have made abundant achievements in exploring the complex spiral architecture of the LV [Ingels 1997; Goffinet 2009]. The pattern of LV systolic movement was the opposite direction of rotation between apex and base and the result was referred to as twist or torsion. The term twist is defined as net difference at isochronal time point between LV apical and basal rotation along LV longitudinal axis, while torsion is LV twist angle indexed to the distance between apical and basal level. In addition to myocardial thickening and shortening, rotation movement also contributes significantly to LV systolic function. The preserved energy during the systolic period is rapidly released during untwisting and sets an important stage for the upcoming diastolic suction and rapid filling.

Cardiovascular magnetic resonance (CMR) myocardial tagging has been considered the relative standard for the evaluation of torsion, which shows excellent inter- and intra-observer agreements [Castillo 2005]. But the need for additional sequence and time-consuming post-processing impedes its application in routine clinical analysis. The advent of CMR feature tracking (CMR-FT) based on routine steady-state free precession (SSFP) images allows for rapid assessment of LV deformation (strain or torsion) [Hor 2010; Kowallick 2014; Morton 2012]. However, there are few reports about the assessment of LV torsion by CMR-FT. Furthermore, although it has been demonstrated that the LV systolic function of patients with poor ejection fraction (<50%) was improved after CABG, no previous studies have assessed the improvement of LV torsion after complete revascularization. Thus, the purpose of this study was to validate the pattern of LV torsion in normal heart by newly applied CMR-FT, quantify the early improvement of LV torsion after CABG, and evaluate its feasibility as a sensitive indicator of cardiac function.

METHODS

Study Population

All patient data used in this study was approved by the institutional review board of our institution. Patients with hemodynamic instability, persistent arrhythmia (atrial fibrillation or pre-mature ventricular beats), or other contraindications to MRI (previous percutaneous coronary intervention,

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Table 1. Patient Characteristics

	Normal (n = 54)	MI patients (n = 36)	χ^2/t	*P*
Male, n	33	22	0.0487	.83
Age, years	43.1 ± 15.4	55.8 ± 10.3	-4.339	<.01
Height, cm	167.4 ± 7.7	170.0 ± 4.7	-1.812	.08
BMI, kg/m^2	23.5 ± 4.4	23.8 ± 2.2	-0.378	.07
Systolic blood pressure, mmHg	125.9 ± 14.4	115.9 ± 26.0	2.342	.02
Heart rate, beats/min	73.2 ± 9.8	77.7 ± 6.9	-2.387	.02
Smoking history, n	9	18	11.42	.00
Diabetes mellitus, n	5	14	11.38	.00
Hyperlipidemia, n	6	21	22.93	.00
Cerebral infarction history, n	0	8	13.17	.00
NYHA class, n				
I	54	5		
II	–	11		
III	–	15		
IV	–	5		
Left main lesion, n	–	8		–
Triple vessel disease, n	–	31		–

Data are presented as the mean ± SD where indicated. BMI indicates body mass index; NYHA, New York Heart Association.

pacemaker or implantable defibrillator, or severe claustrophobia) were excluded from the study. Fifty-four healthy adult volunteers (43.1 ± 15.4 years, 33 male patients) and 36 CAD patients with previous myocardial infarction (MI) and LV ejection fraction (EF) between 30%-50% were included in this study and received CMRI preoperatively (18.2 ± 19.9 days before CABG, median 13 days) and at least 90 days after CABG (237.6 ± 99.1 days postoperatively, median 245.5 days) The demographic characteristics of the volunteers and patients are summarized in Table 1.

Cardiovascular Magnetic Resonance

CMR studies were performed on a 1.5-Tesla whole body scanner (GE Sigma HD Twin, Milwaukee, WI, USA) using a dedicated 8-channel phased-array cardiac coil. After survey scans, the FIESTA cine, a retrospectively ECG-gated balance steady state free procession sequence, was acquired in a single breath hold during end expiration for 12-16 seconds. The scan planes included 10-14 continuous slices in short axial view to cover the whole heart, one slice in horizontal long-axial view (4-chamber view), one slice in vertical long-axial view (2-chamber long-axial view) and one slice in left ventricular outflow tract view (LVOT) adherent to the

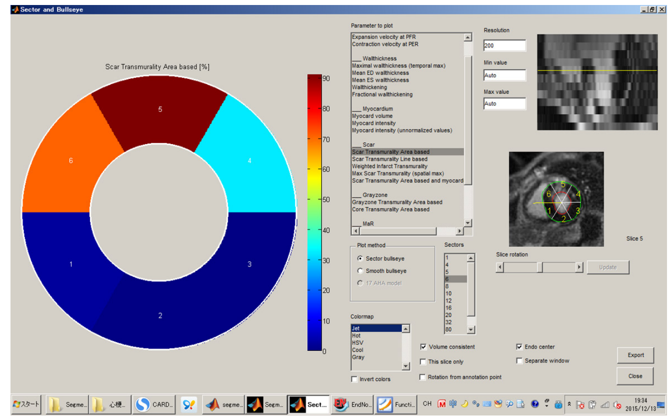

Figure 1. Transmurality of scar calculated from LGE image in the short-axis view. Scar is 100% transmural in the middle part of the anterior wall extending to the segmental and lateral part of the left ventricular. Calculation performed with the Segment software.

AHA/ACC recommendation. The parameters were as follows: slice thickness 8mm, repetition time 3.2 ms, echo time 1.5 ms, flip angle 60 degrees. The contrast-enhanced images were acquired 15 min after the administration of gadopentate dimeglumine (Gd-DTPA) (0.1 mmol/kg) at the same slice positions as the cine-images. Each R-R interval was divided into 24 cardiac phases and 16 k-space lines (view per segment) were filled for a phase in each RR interval. The field of view was 28 cm-35 cm and the matrix was 224 × 192, yielding a resolution of 1.3 mm-1.5 mm.

LV Function and Infarct Size Evaluation

A computer freeware Segment (http://segment.heiberg.se) was used to determine left ventricular scar transmurality, end-diastolic, and end-systolic volumes as well as ejection fraction. Myocardial scar can be visualized in late gadolinium enhanced cines. The scar transmurality was determined in short axis view using Segment (Figure 1), and the infarct areas were in this setting defined as segmental scar areas. Dysfunction segments (mild hypokinesia or worse) were graded according to peak LGE transmurality in end-diastole as follows: A. <1%; B. 0-25%; C. 25%-50%; D. 50%-75%; E. >75%. A scar transmurality ≥ 75% was regarded as transmural.

CMR Feature Tracking

CMR-FT was performed by semi-automated CMR-FT software (Cardiac Performance Analysis MR, TOMTEC Imaging Systems, Munich, Germany) on SSFP sequences of the short-axis views. This feature tracking system has been described recently as used for analyzing cardiac strain and torsion [Hor 2010; Kowallick 2014]. The endocardium was manually contoured on an end-diastolic image and then the software automatically traced the contours for each frame of the cardiac cycle. Minor manual adjustment was performed if LV segments were tracked inappropriately after visual assessment during cine loop playback. The contour of LV endocardium was divided into 48 segments and the program calculates rotation for each of the 48 segments in one view

Table 2. Scar Size and Global Volumes of Left Ventricle

Variables	Normal (n = 54)	MI patients (n = 36)	χ^2/t	*P*
Cine-MRI				
LVEDV, mL	136.1 ± 21.2 (102-172)	209.8 ± 64.3 (108-319)	-7.827	.00
LVESV, mL	65.8 ± 9.6 (45-90)	163.5 ± 41.2 (95-217)	-16.799	.00
LVEF, %	62.9 ± 5.0 (54-71)	27.9 ± 8.5 (17-42)	24.581	.00
LGE-MRI				
LV mass, g	129.1 ± 23.4 (90-170)	147.2 ± 44.6 (101-252)	-2.513	.014
LV scar, %	–	29.7 ± 9.1 (11.1-41.1)		
Transmurality	No. of segments	No. of segments		
<1%	972	466		
1%-25%	–	21		
25%-50%	–	36		
50%-75%	–	50		
>75%	–	75		

Data are presented as the mean ± SD where indicated. LV indicates left ventricle; LVEDV, left ventricular end-diastolic volume; LVESV, left ventricular end-systolic volume; LVEF, left ventricular ejection fraction.

[Meyer 2014]. The highest positive value of apical rotation is defined as peak apical rotation and the highest negative value of basal rotation is defined as peak basal rotation. The 17-segments LV model was applied to analyze rotation data and this allowed calculation of mean rotational value for apical and basal levels.

LV Torsion, Rotation, and Rotational Velocity

One cardiac cycle was selected for analysis. Referring to previous studies [Goffinet 2009; Knudtson 1997], viewed from LV apex, counterclockwise was regarded as positive and clockwise was denoted as negative. Rotation and rotational velocity at apical and basal levels were derived. Twist and recoil are the net difference between the apex and base [Esch 2009]. LV torsion is calculated as LV twist divided by the distance between selected apical and basal level.

Statistical Analysis

Averages, SDs were calculated for each group. Continuous variables are expressed in mean ± SD. The intra- and inter-observer reliabilities were assessed using the Intra Class Correlation Coefficient (ICC) with a 2-way random model with absolute agreement and Bland Altman plots. An ICC ≥ 0.70 was considered to be acceptable. The related-samples Wilcoxon signed rank test was used when the data was not normally distributed. A *P* value of ≤ .05 was considered significant [Wu 2014].

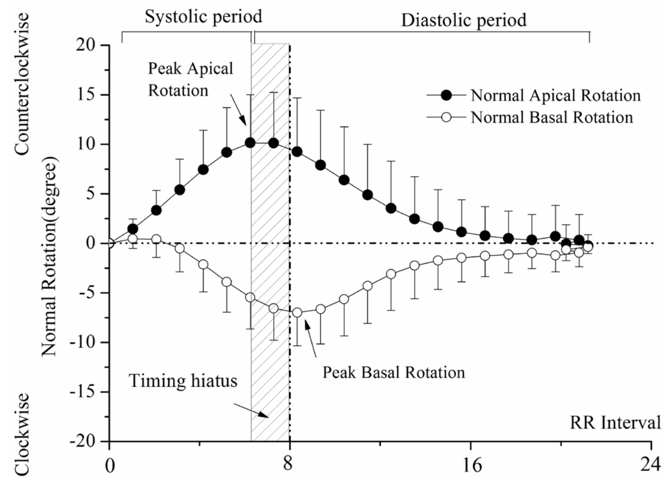

Figure 2. Patterns of basal and apical rotations in normal hearts.

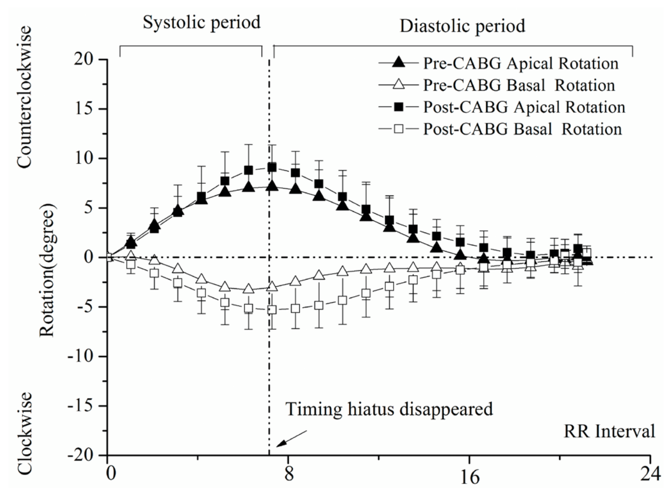

Figure 3. Preoperative and postoperative rotation parameters of patients.

RESULTS

Patient Population

Table 1 shows the baseline characteristics of the normal subjects and patients with MI. Compared with the normal group, patients with MI had worse NYHA cardiac function and had more comorbidities. Table 2 demonstrated scar size was on average 29.7 ± 9.1% of the left ventricle in the scar patients. Fifteen of the 36 patients had a scar percentage exceeding 30%, which is regarded as prognostically unfavorable. In the scar group, scar area was >50% in the anterior segments and 6% in the remote segments.

Normal Rotation Parameters

Patterns of basal and apical rotations during the cardiac cycle are reported in Figure 2. In normal hearts, the

Table 3. Rotation Parameters of Normal Group and Patients

	Normal (n = 54)	Pre-CABG (n = 12)	Post-CABG (n = 12)
Apical rotation (°)	10.2 ± 4.8	7.0 ± 2.6*	9.4 ± 2.4†
Basal rotation (°)	-7.0 ± 3.3	-3.1 ± 2.3*	-5.8 ± 2.0†
Apical twisting angular velocity (°/s)	51.1 ± 30.5	36.0 ± 14.2	38.1 ± 11.3
Apical untwisting angular velocity (°/s)	-38.6 ± 28.1	-29.1 ± 22.6	-29.5 ± 10.2
Basal twisting angular velocity (°/s)	-43.1 ± 22.8	-23.3 ± 13.8	-25.3 ± 16.8
Basal untwisting angular velocity (°/s)	29.4 ± 26.9	11.2 ± 17.3	19.9 ± 16.1
Torsion (°/cm)	5.8 ± 2.7	2.5 ± 0.9*	3.6 ± 1.2†*

Data are presented as mean ± SD. *$P \leq .05$, significantly different from normal group. †$P \leq .05$, significantly different from pre-CABG group.

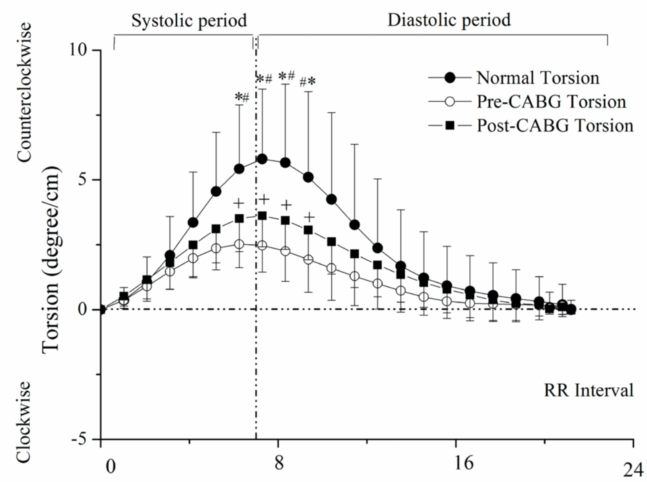

Figure 4. Torsion was calculated for healthy group and patients preoperatively and postoperatively. *$P \leq .05$, compared with preoperative torsion. #$P \leq .05$, compared with postoperative torsion.

apex rotated counterclockwise in systolic period with the peak rotation of 10.2 ± 4.8°, and the time-to-peak value was 234.1 ± 42.3 ms. The peak twisting and untwisting velocities of apex were 51.1 ± 30.5°/s and -38.6 ± 28.1°/s. The base rotated clockwise as the peak rotation was 7.0 ± 3.3° with the peak time of 312.1 ± 56.20 ms, and the peak twisting and untwisting velocities of base were -43.1 ± 22.8°/s and 29.4 ± 26.9°/s. The rotation degree of apex was significantly greater than that of the base, and the time hiatus of untwisting between apex and base was 78.0 ± 14.0 ms, during which period the heart recoils and its suction sets the stage for the following rapid filling period.

Rotation and Torsion Improvements in Patients Receiving CABG

Figure 3 demonstrates improvement from preoperative rotation parameters to postoperative ones. The apical/basal peak rotations were significantly decreased preoperatively compared with the normal group (Table 3). Torsion was significantly impaired in patients with MI, relative to the healthy group, and significantly improved after CABG, but was still lower than the normal group (Figure 4).

LV torsion and ejection fraction

Figure 5 shows strong correlation between LV torsion and LV ejection fraction (LVEF) ($r = 0.83$, $p < 0.05$). By self-comparison, the improvement of torsion was significant ($p < 0.05$). However EF, the traditional indicator of cardiac function, didn't show significant improvement ($p > 0.05$). (Figure 6)

Reproducibility

All rotation parameters were reproducible on an intra-observer and inter-observer level. Figure 7 displays the Bland-Altman plots showing the 95% confidence intervals of the difference between the inter- and intra-observer measurements. Observer variability was good for torsion value as determined by 95% confidence intervals of the difference. The interclass correlation coefficient (ICC) with 95% confidence intervals for intra-observer was 0.965 (0.927-0.983), and for inter-observer was 0.980 (0.957-0.990).

DISCUSSION

The torsion movement of the LV is a complex and interactive result of the difference of LV apical rotation relative to basal rotation. LV torsion is ascribed to the helical arrangement of the myocardial fibers which drive the LV apex to move counterclockwise and the base clockwise viewed from the apex.

The earliest evaluation of torsion was provided by the magnetic resonance imaging tagging method, which, however, was limited in clinical use mainly due to technical difficulties such as high cost, additional tagging sequences, and prolonged post-processing. The advent speckle tracking by echocardiography has made it convenient to evaluate cardiac rotation bedside. But speckle tracking is affected by inadequate acoustic windows [Orwat 2014]. In recent years, cardiac magnetic resonance based on feature tracking (CMR-FT) analysis has become a convenient and reproducible technique without the need for tagged images [Hor 2010; Kowallick 2014; Hor 2011].

Torsion Derived from CMR-FT

In normal hearts, the preserved torsion forces are released during the early diastolic period, which was reported as 80-90 ms by previous studies [Hristov 2006; Buckberg 2011], similar to our results studied by CMR-FT in the research. This interval was considered to be

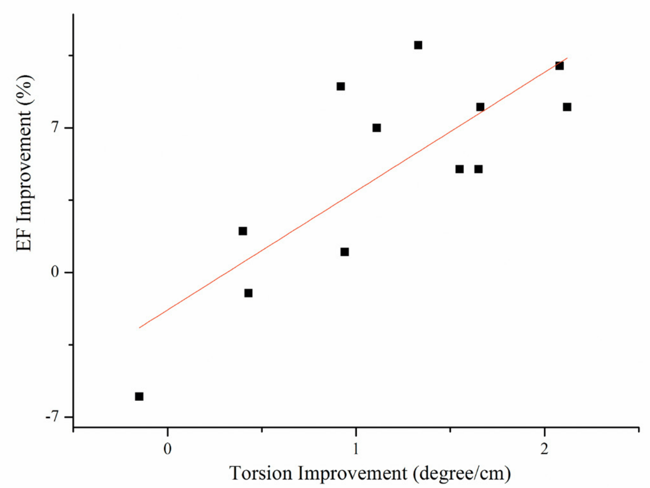

Figure 5. Torsion improvement correlates positively with EF improvement (r = 0.83, *P* < .05).

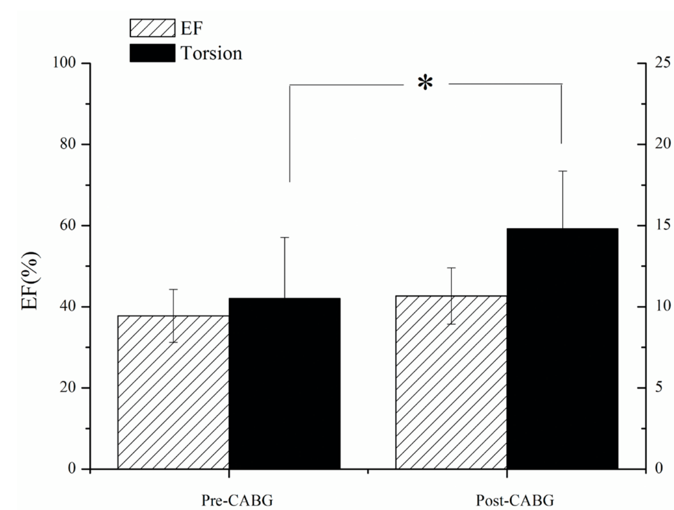

Figure 6. Self-comparison showed the improvement of torsion was significant (*P* < .05). But ejection fraction didn't show significant improvement (*P* > .05).

important for LV suction and early rapid filling [Rademakers 1992]. Compared with the normal group, this interval almost disappeared in patients with MI, suggesting that the diastolic function was impaired. Thus the consideration of treatment for these patients should be given to both the improvement of systolic function and prolongation of the early diastolic interval.

Currently, there is a lack of standardization for the measurement of twisting movement of LV, and torsion has been calculated as net difference of the rotation between apex and base, rotation index (degree/cm) and torsional shear angle (degrees). We suggest rotation per length (rotation index) as the calculation of LV torsion since this takes into account that LV rotation is highly dependent on the site of apical or basal levels, as previous studies have shown.

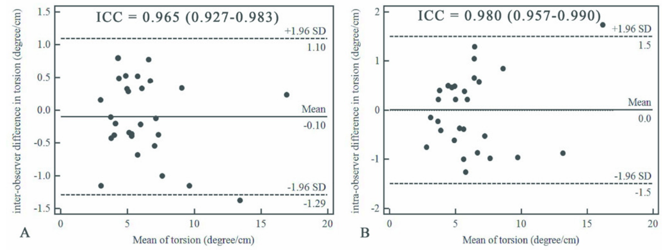

Figure 7. Bland-Altman plots demonstrating the reproducibility of CMR-FT. Interclass correlation coefficients (ICC) with 95% confidence intervals are provided.

Torsion as a Sensitive Index of Cardiac Function

Coronary artery bypass grafting (CABG) has been proven to be an effective option for the improvement of poor LV function [Hovnanian 2010; Shapira 1995]. The abnormal LV function after MI may not necessarily represent irreversible myocardial necrosis, while instead, the hibernating myocardium may shed new light for the enhancement of LV function after MI. Thus, one of the most important tasks lies in the evaluation of LV contractility. Traditional quantification indices of LV systolic function include ventricular volumes, ejection fraction, and end-diastolic/systolic volume index, etc, and these indicators are on the prerequisite that the whole LV contract simultaneously, or in synchrony. However, both the structural anisotropy and the heterogeneity of mechanical shortening and lengthening depicted by imaging modality have been revealed by studies [Hansen 1988; Matsumoto 2012; Pravdin 2013]. Previous studies of LV fiber orientation and ventricular geometry by cylindrical, spherical, or ellipsoidal reference ventricles have demonstrated that either circular or "constrictor" oriented fibers could not explain the high efficient ejection fractions in these theoretical mathematical models. Thus, a class of helical fiber is introduced from which any desired ejection fraction can be generated. The contraction of the helical fiber results in two opposite basal and apical rotation, which leads to LV wringing motion, and quantification of LV rotation or torsion is expected to be useful for assessing LV systolic function, since it conforms to cardiac physiological movement. Animal and clinical experiments have showed LV rotation is sensitive to changes both in regional and global LV systolic function. This present study finds that CABG could improve patients' apical and basal rotation, and the torsion was more sensitive to the cardiac function improvement compared with traditional EF in the early stage (3 months to 1 year) after CABG. On the other hand, LV torsion correlates well with EF and both indicators illustrate the improvement of cardiac function after complete revascularization.

Reproducibility

Previous studies by CMR-FT focused on LV strain measurements, and the reproducibility varies more or less in the ensuing studies in the quantification of myocardial deformation. Therefore, we have studied the intra- and inter-observer variability of torsion, and Bland-Altman plots showed that almost all data points were within the confidence limits. ICC for intra-observer and inter-observer were provided and reproducibility of the results was acceptable.

Conclusions

With the help of newly applied cardiovascular magnetic resonance feature tracking (CMR-FT) software, we quantified the torsion movement in normal hearts, and the time hiatus measured as 70-80 ms is essential to cardiac relaxation and suction process. Reproducibility was good for torsion parameters. By evaluating the effects of CABG on torsion movement, we found CABG could improve patients' apical and basal rotation, and the torsion was more sensitive to the cardiac function improvement compared with traditional EF. The quantification of systolic and diastolic function by feature tracking may have potential clinical and research applications, and its clinical utility and diagnostic value need to be verified by large cohort studies in the future.

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