**Name of Journal: *World Journal of Cardiology***

**ESPS Manuscript NO: 32035**

**Manuscript Type: Minireviews**

**Feature tracking cardiac magnetic resonance imaging: A review of a novel non-invasive cardiac imaging technique**

Rahman ZU *et al.* Feature tracking cardiac magnetic resonance imaging

## Zia Ur Rahman, Pooja Sethi,Ghulam Murtaza, Hafeez Ul Hassan Virk, Aitzaz Rai, Masliza Mahmod, Jeffrey Schoondyke, Kais Albalbissi

 **Zia Ur Rahman, Pooja Sethi**,**Jeffrey Schoondyke, Kais Albalbissi**, Department of Internal Medicine, Divison of Cardiology, East Tennessee State University, Johnson City, TN 37064, United States

**Ghulam Murtaza,** Department of Internal Medicine, East Tennessee State University, Johnson City, TN 37064, United States

#### Hafeez Ul Hassan Virk, Department of Internal Medicine, Icahn School of Medicine at Mount Sinai-St Luke’s West Hospitals, New York, NY 10029, United States

#### Aitzaz Rai, Department of Internal Medicine, Green Templeton College, University of Oxford OX2HG, United Kingdom

**Masliza Mahmod**, Department of Cardiovascular Medicine, University of Oxford, Oxford OX2HG, United Kingdom

**Author contributions:** Rahman ZU, Sethi P and Murtaza G performed the majority of the writing, prepared the figures and tables; Hafeez Virk HUH and Rai A performed data accusation and writing; Mahmod M and Schoondyke J provided the input in writing the paper; Albalbissi K designed the outline and coordinated the writing of the paper.

**Conflict-of-interest statement:** There is no conflict of interest associated with any of the senior author or other coauthors contributed their efforts in this manuscript.

**Open-Access:** This article is an open-access article which was selected by an in-house editor and fully peer-reviewed by external reviewers. It is distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited and the use is non-commercial. See: <http://creativecommons.org/licenses/by-nc/4.0/>

**Manuscript source:** Unsolicited manuscript

**Correspondence to:** **Ghulam Murtaza, MD,** Department of Internal Medicine, East Tennessee State University, 325 N State of Franklin Rd, Johnson City, TN 37064, United States. murtazag@etsu.edu

**Telephone:** +1-423-7411863

**Fax:** +1-423-9794134

**Received:** December 22, 2016

**Peer-review started:** December 30, 2016

**First decision:** February 17, 2017

**Revised:** March 1, 2017

**Accepted:** March 23, 2017

**Article in press:**

**Published online:**

**Abstract**

Cardiovascular disease is a leading cause of morbidity and mortality globally. Early diagnostic markers are gaining popularity for better patient care disease outcomes. There is an increasing interest in noninvasive cardiac imaging biomarkers to diagnose subclinical cardiac disease. Feature tracking cardiac magnetic resonance imaging is a novel post-processing technique that is increasingly being employed to assess global and regional myocardial function. This technique has numerous applications in structural and functional diagnostics. It has been validated in multiple studies, although there is still a long way to go for it to become routine standard of care.

**Key words:** Feature tracking cardiac magnetic resonance imaging; Feature tracking; Myocardial tagging

**© The Author(s) 2017.** Published by Baishideng Publishing Group Inc. All rights reserved.

**Core tip:** Feature tracking cardiac magnetic resonance imaging (FT-CMR) is novel non-invasive imaging technique that is being used commonly in assessment of different cardiac disorders. FT-CMR utilizes standard steady-state free precession sequences and is simpler, more practical and easily available. It has been validated in multiple studies. The objective of our literature review is to look at the current literature regarding validation, normal and abnormal values, advantages and limitations of FT-CMR in research and clinical trials.

Rahman ZU, Sethi P,Murtaza G, Virk HUH, Rai A, Mahmod M, Schoondyke J, Albalbissi K. Feature tracking cardiac magnetic resonance imaging: A review of a novel non-invasive cardiac imaging technique. *World J Cardiol* 2017; In press

**INTRODUCTION**

Cardiovascular diseases constitute a major global public health burden. It accounts for about one third (30.9%) of patient mortality worldwide[1]. Due to increasing economic burden and shrinking resources, there is a major shift in strategy towards prevention and early detection of cardiac disease worldwide.

Among non-invasive diagnostic techniques, cardiac magnetic resonance imaging (MRI) is a gold standard. Strain imaging on cardiac magnetic resonance imaging (CMR) through myocardial tagging was in vogue since the ground-breaking work of Zerhouni in 1988. Since then many imaging sequences have been designed to measure the global and regional function of myocardium. However, most of these sequences are fraught with fading of tag lines in diastole, long the breath-hold time which are cumbersome in acutely ill and advanced cardiac failure and those with coexistent pulmonary diseases.

Strain imaging using Echocardiographic measurements obtained using tissue Doppler is limited by noise interference and angle dependency.While speckle tracking has largely overcome these issues, it is often limited by image quality CMR with feature tracking is a novel technique which uses myocardial deformation for global and segmental functional analysis. Feature tracking uses different myocardial strain patterns including longitudinal, radial and circumferential strain measurements for global and segmental functional assessment[2]. Strain on feature tracking is not dependent on loading conditions, unlike ejection fraction, and it is actually a ratio of initial and final myocardial lengths during different portions of myocardial cycle. Strain is equal to L - LO/LO, where L is final length and Lois initial length.

Strain is a measure of myocardial deformation, longitudinal strain is measured in long axis while circumferential and radial strains are measured in short-axis. As cardiac magnetic resonance feature tracking (CMR-FT) is less time consuming due to no prolonged post processing times involved, it may have a better future value in quick assessment of myocardial mechanics[2]. It has been well studied in last few years and it has shown to play a great role in the diagnosis of multiple cardiac conditions as detailed below. The purpose of our literature review was to assess its integration in routine clinical care for the assessment of myocardial function to avoid unnecessary invasive diagnostic, *e.g.*, intravascular ultrasound and cardiac catheterization.

**VALIDATION OF CMR AS NOVEL IMAGING MODALITY**

Feature-tracking (FT) is a novel technology which is used to calculate strain for the assessment of cardiovascular disease, is not a validated technique at the moment, against a standard myocardial tagging analysis for any strain parameter. It needs to be validated before incorporating it into routine clinical practice. We will compare CMR-FT with other diagnostic modalities such as echocardiogram to assess its equivalence versus superiority or inferiority. Echocardiographic measurements obtained using tissue Doppler imaging are limited by noise interference and angle dependency.While speckle tracking has largely overcome these issues, it is often limited by image quality In order to label it as standard of care, we also need to look for inter study, inter and intra observer reproducibility of CMR feature tracking (Table 1).

Taylor *et al*[3] studied 20 healthy volunteers and measured myocardial strain using FT. They found FT highly reproducible within operators and needed a short analysis time of 3 ± 1 min.

Augustine *et al*[4] used feature tracking in 145 healthy individuals to measure different myocardial deformation parameters including radial, circumferential and longitudinal strain, and segmental levels based on age and gender and recorded the normal values. They found these values to be similar when compared to prior studies based on age and gender. They also used myocardial tagging in 20 of these subjects to measure these same values and compared them with those obtained by feature tracking. Feature tracking measurements of circumferential but not longitudinal or radially directed global strain showed reasonable agreement with myocardial tagging and acceptable inter-observer reproducibility. Similarly, Schuster *et al*[2] studied feature tracking measurements in 20 healthy subjects with 2 sets of measurements, one at baseline and other after 4 wk. They found that FT-CMR had reasonable intra observer reproducibility in different groups of individuals. It was most reproducible for left ventricular circumferential strain measurements while it was least reproducible for right ventricular longitudinal strain.

Use of Feature tracking was not only studied in primary cardiovascular disease patients but was also used to study left ventricular radial and circumferential strain to assess anthracycline induced cardiotoxicity. Both circumferential and radial strain detected subclinical cardiac dysfunction in this cohort. Feature tracking was compared with harmonic phase imaging analysis (HAARP). Circumferential strain was found to be a robust and reproducible index in this study while radial strain did not show much promise[5].

To assess the reproducibility of myocardial strain, FT was compared with tagging in a small patient cohort of left bundle branch block (LBBB) and hypertensive cardiomyopathy. It concluded that peak circumferential strain and time to peak circumferential strain are not good indices in this patient population. Although it was well designed study, but due to small sample size (*n* = 20) it would be far from conclusive[6].

Another well designed study on large cohort (*n* = 233) Duchene Muscular Dystrophy (DMD) patients stratified into various groups based on EF and late gadolinium enhancement (LGE) after age and gender matching. There was a good correlation between CMR-FT and HAARP for the mean circumferential strain values (-13.3% ± 3.8% for CMR-FT *vs* 13.6% ± 3.4%) for HAARP with an r = 0.899[7].

Morton *et al*[8] imaged 16 healthy individuals with CMR feature tracking 3 times in a single day and different time points to look for inter-study reproducibility. They concluded that CMR-FT had good inter-study reproducibility for global strain analysis while it was poor for segmental strain. Though, they did not find any diurnal variation in strain measurements[8].

Kempny *et al*[9] used feature tracking for biventricular myocardial function assessment in 28 patients of repaired Teratology of Fallot (ToF) and healthy 25 controls and compared it with speckle tracking echocardiography (STE) and simple endocardial border delineation (EBD). They found close agreement between right and left ventricular global strain. Inter observer agreement for features tracking and STE was moderate for longitudinal left ventricular global strain while feature tracking showed better inter observer reproducibility for circumferential or radial left ventricular and longitudinal right ventricular global strain when compared to STE. Feature tracking showed poor reproducibility for regional strain. The relative systolic length change of endocardial border as measured by EBD was similar to feature tracking global strain[9]. Similarly studying similar population and comparing this novel technique with 2D echocardiography, Padiyath *et al*[10] studied myocardial mechanics in 20 patients with Teratology of Fallot and 20 healthy controls using 2D STE echocardiography and FT-CMR. They found reasonable agreement between the 2 modalities in measurement of global circumferential strain and global longitudinal strain for the left ventricle (9.5% and 16.4% inter modality variability, respectively) while right ventricular global longitudinal strain had an inter modality variability of 25.7%. Also, the global radial strain measurements had high inter modality and inter observer variability[10]. When compared with 2D echocardiography for right ventricular strain assessment, CMR-FT showed reasonable agreement with 2D echo in these assessments[11].

In hypertrophic cardiomyopathy (HCM) patients, feature tracking was compared with myocardial tagging in 13 normal subjects and 11 patients of HCM patients, showing closer agreement between 2 modalities in measuring time to peak strain while agreement was more modest in measuring magnitude of the peak strain[12]. Orwat *et al*[13] studied feature tracking myocardial measurements in 20 healthy volunteers (ten male, mean age 24 ± 3 years) and 20 patients with HCM (12 male, mean age 47 ± 19 years) and compared them with trans-thoracic echocardiogram with speckle tracking. They found decent agreement between left ventricular longitudinal strain measurements between the 2 modalities while the agreement for circumferential strain and strain rate was not encouraging. There was high reproducibility for left ventricular peak global strain measurements as compared to strain rate[13].

Validity of FT-CMR was also studied in patients with recent or past myocardial infarction patients. Gao *et al*[14] examined 3 healthy controls and 41 patients with either recent or past MI to assess left ventricular strain and compared with DENSE (displacement encoding with stimulated echoes in cardiac functional MRI). He found good agreement in peak circumferential and peak radial strain values in patient population although peak radial strain measurements in healthy patients was overestimated in healthy controls when using cine CMR as compared to DENSE[14]. Also in aortic stenosis patients (*n* = 30), a reasonable agreement was found in deformation measurements as measured from myocardial strain using FT as compared to tagging technique[15]. In another study, Schneeweis *et al*[16] measured circumferential strain by using speckle tracking echocardiography (STE), FT and myocardial tagging and compared these three modalities. They found that FT and Tagging had moderate agreement in global circumferential strain analysis while agreement was poor for segmental analysis. No agreement was found between CMR (FT and MT) based global and segmental circumferential strain measurements and ST based values[16].

Anwar *et al*[17] studied 15 single ventricle Fontan (“Fontan” is a procedure done in pediatric patients who have 1 functional ventricle when born) patients with FT and compared it with tagging. They found moderate agreement between these 2 modalities in the assessment of circumferential strain[17].

**REFERENCE VALUES OF FT-CMR FOR NORMAL AND DISEASED PATIENTS**

Feature tracking imaging could reliably be used to assess myocardial function in patients with early dysfunction. Multiple parameter datasets are available for radial systolic strain values, circumferential strain values, circumferential strain, longitudinal endocardial systolic strain, longitudinal strain and segmental reproducibility for systolic strain measurements[18]. Similarly, Taylor *et al*[19] studied the values for feature tracking in a cohort of 108 cardiomyopathy patients and 55 normal healthy controls. Healthy controls (*n* = 55, age: 42.9 ± 13 years, LVEF: 70% ± 5%, QRS: 88 ± 9 ms) and patients with cardiomyopathy (*n* = 108, age: 64.7 ± 12 years, LVEF: 29% ± 6%, QRS: 147 ± 29 ms) underwent FT-CMR for the assessment of the circumferential uniformity ratio estimate (CURE) and radial uniformity estimate ratio (RURE) based on myocardial strain (both CURE and RURE: 0 to 1; 1 = perfect synchrony). CURE (0.79 ± 0.14 *vs* 0.97 ± 0.02) and RURE (0.71 ± 0.14 *vs* 0.91 ± 0.04) were lower in patients with cardiomyopathy than in healthy controls (both P < 0.0001). CURE [area under the receiver-operator characteristic curve (AUC): 0.96], RURE (AUC: 0.96) and an average of these (CURE: RURE AVG, AUC: 0.98). They concluded that measures like CURE and RURE provide absolute differentiation between patients with cardiomyopathy and normal healthy controls with a sensitivity of 90%, specificity of 98% at a cut-off of 0.89[19]. Buss *et al*[20] and Shang *et al*[21] measured reference values in 110 healthy adult patients and 115 healthy pediatric patients. Their work was based on the fact that some observational studies of left ventricular function in adults suggest that global longitudinal strain correlate with EF, and is superior to EF as a predictor of outcome. Also, Kadiyala *et al*[22] measured values of myocardial strain in 60 normal subjects and tabulated them for reference.

## *Features tracking algorithm*

Proto-type software is TomTec (Diogenes Medical, Germany). Different algorithms are available for strain measurement. Elnakib *et al*[23] suggested the algorithm shown in Table 2.

# *Clinical applications of feature tracking*

Assessment of left ventricular function is a key application of CMR. Feature tracking imaging is a fast and rapid method that provides an objective and reliable measurement of left ventricular function. CMR-FT is a novel promising technique to diagnose structural and functional heart disease. It provides a rapid a method to diagnose these conditions without long and watchful waiting processing times[3]. In 1 study[7], analysis of a complete data set using Feature Tracking was quicker than by tagging (8.8 ± 4.7 min *vs* 15.4 ± 4.9 min, *P* < 0.05). It does not require any extra imaging sequences and can be applied to any imaging sequence.

**Structural heart disease:** In single ventricular patients, feature tracking could help to identify ventricular dysfunction based on specific type of defect present. Moore *et al*[24] collected the data from 25 control subjects and 30 patients with single ventricle (right or left) and used feature tracking for mechanical dyssynchrony and strain analysis in these patients. They concluded that analysis of circumferential strain is abnormal in single ventricle patients despite normal ejection fraction[24]. In patients after repair of coarctation of aorta, FT can detect early systolic dysfunction. Kutty *et al*[25] used FT to identify abnormal strain patterns as indication of early systolic dysfunction despite normal ejection fraction in 81 patients 10-13 years after repair for coarctation of aorta. It was noted that global longitudinal strain measurements were worse in the presence of left ventricular hypertrophy[25]. FT was found to be better, fast and reliable method in quantification of wall mechanics and strain after 10 healthy subjects were examined with CMR-FT to for quantitative wall motion assessment during intermediate dose dobutamine stress CMR[26]. In addition to diagnosing early cardiac dysfunction in structural heart disease patients, FT allows quantitative elaboration of myocardial tissue and blood flow[27]. Fifteen patients with ischemic cardiomyopathy were enrolled in 1 study for viability assessment *via* feature tracking measurements. FT imaging was done both at rest and during low-dose dobutamine stress. Feature tracking was found to be a reliable method for quantitative assessment of myocardial viability in patients with ischemic cardiomyopathy[28]. Feature tracking was also useful in identifying higher indexes of left ventricular dyssynchrony which were associated with ventricular tachycardia and death in patients with repaired tetralogy of Fallot[29]. This technique was also used to study the impact of transcatheter pulmonary valve placement on biventricular strain and synchrony in patients with right ventricular outflow tract conduit dysfunction which showed improved right and left ventricular global strain and left ventricular synchrony, showing the value of feature tracking in this patient population[30]. Role of feature tracking in the diagnosis of muscular dystrophy associated cardiomyopathy has been evaluated in some studies. Rosales *et al*31] found the role of FT in diagnosis of Limb Girdle Dystrophy associated cardiac dysfunction including cardiomyopathy with systolic dysfunction, myocardial fibrosis and diastolic dysfunction.

**Ischemic cardiomyopathy:** Usefulness of FT is not only limited to structural heart diseases, it has been studied extensively in patients with ischemic cardiomyopathy secondary to coronary artery disease. In a study by Buss *et al*[32], FT was used in 74 patients with first STEMI 2-4 d after reperfusion. Circumferential strain analysis provided an objective method in the assessment of infarct size[32]. They found similar utility of FTI in another study of 54 patients with first time STEMI[33].

**Non-ischemic cardiomyopathies:** FT doesn’t limit its usefulness in ischemic and structural heart disease patients, non-ischemic cardiomyopathies can also be managed early in the course if FT is used. Breuninger *et al*[34] used FT to assess myocardial strain in 88 patients with dilated cardiomyopathy and 30 healthy controls and found it to be reliable in analyzing global myocardial function. Steinmetz *et al*[35] studied 26 patients with uncorrected Ebstein’s anomaly and 10 healthy controls with FT to measure right and left ventricular deformation and dyssynchrony which showed RV intraventricular dyssynchrony and reduced RV global strain in patients with Ebstein’s Anomaly as compared to healthy controls. Buss *et al*[33] studied 210 patients with dilated cardiomyopathy with FT and noted that LV longitudinal strain assessment *via* FT was an independent predictor of patient survival and thus a helpful diagnostic tool for risk stratification in this patient population beyond clinical parameter and standard CMR[32]. Similarly, in hypertrophic cardiomyopathy (HCM) patients, Smith *et al*[36] used FT to follow 30 HCM pediatric patients (14.1 ± 3.2 years) and the relationship of LGE (present in 17 of those patients) to adverse clinical outcome (defined as cardiac death non sustained Ventricular tachycardia, ventricular fibrillation and appropriate AICD discharge) over a period of 26.9 mo. They found LGE presence in these pediatric patients comparable to adult population in terms of decreased myocardial strain and adverse clinical outcome[36]. Thavendiranathan *et al*[37] studied 30 patients with myocarditis and takotsubo cardiomyopathy with CMR and feature tracking and they found it a rapid and reliable method to diagnose myocardial injury in these conditions[37]. Petryka *et al*[38] used FT in 137 children with known or suspected HCM, DCM or LV non compaction to measure strain and its prognostic significance. Circumferential Strain measurements in these patients were thought to be valuable in predicting adverse outcome.

Advanced heart failure: Cardiac resynchronization therapy (CRT) provides both morbidity and mortality benefit in advanced heart failure patients. Measurement of left ventricular mechanical dyssynchrony in these patients might provide prognostic information along with QRS duration. Onitsha *et al*[39] studied 72 patients to assess left ventricular dyssynchrony using CMR-FT and speckle tracking echocardiography with promising results concluding FT as a reasonable technique for patients with more marked dyssynchrony.

**Cardio-oncology:** Use of feature tracking for the diagnosis of chemotherapy-induced cardiomyopathy has been established in multiple studies[5,40]. In another study, Kowallick *et al*[41] used this technique to measure left atrial mechanics in 10 healthy controls, 10 patients with HCM and 10 patients with heart failure with preserved LVEF (HFpEF). They concluded that FT reliably differentiated between healthy controls and patients with impaired left ventricular relaxation based on LA longitudinal strain and strain rate measurements[41].

**Other diseases:** A small study identified the role of feature tracking in diagnosing myocardial abnormalities in patients with Churg-Strauss syndrome and Wegener’s Granulomatosis and in clinical remission with normal EKG and transthoracic echocardiogram[30]. Feature tracking could also be useful in the diagnostic workup of left ventricular hypertrophy and the detection of early cardiac involvement in Anderson Fabry's disease which is an X-linked lipid storage disorder (characterized by multi organ involvement and premature death due to cardiac failure, renal failure, stroke and arrhythmias), with potential for therapy monitoring[42]. Strain measurements using feature tracking should play a major role in instituting early therapy for cardiomyopathy in patients with Duchenne Muscular Dystrophy associated cardiomyopathy and other similar cardiomyopathies where abnormal strain patterns precede the systolic dysfunction[43,44]. These measurements could also be helpful in following paroxysmal atrial fibrillation patients after ablation therapy to look for the presence and reversibility of cardiac dysfunction[29]. Bratis *et al*[45] found FT to be helpful in differentiating between normal controls and Kawasaki Disease patents in a study of 29 KD convalescent patients and 10 healthy controls.

**FUTURE DIRECTION**

Despite recent surge in the number of studies looking at this diagnostic modality, we still need large randomized trials. More studies are needed to assess the role of feature tracking in the assessment of right ventricular/right and left atrial dysfunction[11]. Further refinements are needed to overcome poor reproducibility in left ventricular segmental screen measurements and right ventricular strain measurements[27].

**CONCLUSION**

CMR-FT is a new and potentially useful noninvasive technique for measuring myocardial strain from routine cine CMR images using feature-tracking algorithms that were initially designed for echocardiographic strain analysis. FT-CMR tracks tissue voxel motion using standard steady-state free precession (SSFP) sequences and is simpler, more practical and easily available and less time consuming than other CMR-based strain techniques for global and segmental myocardial function analysis. It needs to be further studied and validated for routine use in current clinical practice.

**REFERENCES**

1 **Yusuf S**, Reddy S, Ounpuu S, Anand S. Global burden of cardiovascular diseases: part I: general considerations, the epidemiologic transition, risk factors, and impact of urbanization. *Circulation* 2001; **104**: 2746-2753 [PMID: 11723030 DOI: 10.1161/hc4601.099487]

2 **Schuster A**, Morton G, Hussain ST, Jogiya R, Kutty S, Asrress KN, Makowski MR, Bigalke B, Perera D, Beerbaum P, Nagel E. The intra-observer reproducibility of cardiovascular magnetic resonance myocardial feature tracking strain assessment is independent of field strength. *Eur J Radiol* 2013; **82**: 296-301 [PMID: 23246014 DOI: 10.1016/j.ejrad.2012.11.012]

3 **Taylor RJ**, Umar F, Moody WE, Townend J, Steeds RP, Leyva F. 102 the reproducibility and analysis time of cardiac magnetic resonance feature tracking: potential for clinical application. *Heart* 2013; **99** (suppl 2): A64 [DOI: 10.1136/heartjnl-2013-304019.102]

4 **Augustine D**, Lewandowski AJ, Lazdam M, Rai A, Francis J, Myerson S, Noble A, Becher H, Neubauer S, Petersen SE, Leeson P. Global and regional left ventricular myocardial deformation measures by magnetic resonance feature tracking in healthy volunteers: comparison with tagging and relevance of gender. *J Cardiovasc Magn Reson* 2013; **15**: 8 [PMID: 23331550 DOI: 10.1186/1532-429X-15-8]

5 **Lu JC**, Connelly JA, Zhao L, Agarwal PP, Dorfman AL. Strain measurement by cardiovascular magnetic resonance in pediatric cancer survivors: validation of feature tracking against harmonic phase imaging. *Pediatr Radiol* 2014; **44**: 1070-1076 [PMID: 24760125 DOI: 10.1007/s00247-014-2992-2]

6 **Wu L**, Germans T, Güçlü A, Heymans MW, Allaart CP, van Rossum AC. Feature tracking compared with tissue tagging measurements of segmental strain by cardiovascular magnetic resonance. *J Cardiovasc Magn Reson* 2014; **16**: 10 [PMID: 24450803 DOI: 10.1186/1532-429X-16-10]

7 **Hor KN**, Gottliebson WM, Carson C, Wash E, Cnota J, Fleck R, Wansapura J, Klimeczek P, Al-Khalidi HR, Chung ES, Benson DW, Mazur W. Comparison of magnetic resonance feature tracking for strain calculation with harmonic phase imaging analysis. *JACC Cardiovasc Imaging* 2010; **3**: 144-151 [PMID: 20159640 DOI: 10.1016/j.jcmg.2009.11.006]

8 **Morton G**, Schuster A, Jogiya R, Kutty S, Beerbaum P, Nagel E. Inter-study reproducibility of cardiovascular magnetic resonance myocardial feature tracking. *J Cardiovasc Magn Reson* 2012; **14**: 43 [PMID: 22721175]

9 **Kempny A**, Fernández-Jiménez R, Orwat S, Schuler P, Bunck AC, Maintz D, Baumgartner H, Diller GP. Quantification of biventricular myocardial function using cardiac magnetic resonance feature tracking, endocardial border delineation and echocardiographic speckle tracking in patients with repaired tetralogy of Fallot and healthy controls. *J Cardiovasc Magn Reson* 2012; **14**: 32 [PMID: 22650308 DOI: 10.1186/1532-429X-14-32]

10 **Padiyath A**, Gribben P, Abraham JR, Li L, Rangamani S, Schuster A, Danford DA, Pedrizzetti G, Kutty S. Echocardiography and cardiac magnetic resonance-based feature tracking in the assessment of myocardial mechanics in tetralogy of Fallot: an intermodality comparison. *Echocardiography* 2013; **30**: 203-210 [PMID: 23167248 DOI: 10.1111/echo.12016]

11 **Augustine D**, Suttie JJ, Cox P, Lewandowski AJ, Holloway C, Petersen SE, Myerson S, Neubauer S, Leeson P. CMR right ventricular strain assessment using feature tracking cine images: agreement with echocardiography. *J Cardiovasc Magn Reson* 2012; **14**: 1-2 [DOI: 10.1186/1532-429x-14-s1-p244]

12 **Harrild DM**, Han Y, Geva T, Zhou J, Marcus E, Powell AJ. Comparison of cardiac MRI tissue tracking and myocardial tagging for assessment of regional ventricular strain. *Int J Cardiovasc Imaging* 2012; **28**: 2009-2018 [PMID: 22392105 DOI: 10.1007/s10554-012-0035-3]

13 **Orwat S**, Kempny A, Diller GP, Bauerschmitz P, Bunck ACh, Maintz D, Radke RM, Baumgartner H. Cardiac magnetic resonance feature tracking: a novel method to assess myocardial strain. Comparison with echocardiographic speckle tracking in healthy volunteers and in patients with left ventricular hypertrophy. *Kardiol Pol* 2014; **72**: 363-371 [PMID: 24293146 DOI: 10.5603/KP.a2013.0319]

14 **Gao H**, Allan A, McComb C, Luo X, Berry C. Left ventricular strain and its pattern estimated from cine CMR and validation with DENSE. *Phys Med Biol* 2014; **59**: 3637-3656 [PMID: 24922458 DOI: 10.1088/0031-9155/59/13/3637]

15 **Schneeweis C**, Lapinskas T, Schnackenburg B, Berger A, Hucko T, Kelle S, Fleck E, Gebker R. Comparison of myocardial tagging and feature tracking in patients with severe aortic stenosis. *J Heart Valve Dis* 2014; **23**: 432-440 [PMID: 25803969]

16 **Schneeweis C**, Doltra A, Nasser SB, Hassel J-H, Gräfe M, Wellnhofer E, Schnakenburg B, Berger A, Gebker R, Fleck E, Kelle S. Intraindividual comparison of circumferential strain using speckle tracking by echocardiography versus CMR feature tracking and myocardial tagging in patients. *J Cardiovasc Magn Reson* 2015; **17** (Suppl 1): P340-P340 [DOI: 10.1186/1532-429X-17-S1-P340]

17 **Anwar S**, Fogel EJ, Doddasomayajula R, Davidson A, Keller MS, Harris MA, Whitehead KK, Fogel MA. Feature tracking strain is similar to harmonic phase cardiac magnetic resonance in Fontan patients: a validation study. *J Cardiovasc Magn Reson* 2014; **16** (Suppl 1): P106-P106 [DOI: 10.1186/1532-429X-16-S1-P106]

18 **Andre F**, Steen H, Matheis P, Westkott M, Breuninger K, Sander Y, Kammerer R, Galuschky C, Giannitsis E, Korosoglou G, Katus HA, Buss SJ. Age- and gender-related normal left ventricular deformation assessed by cardiovascular magnetic resonance feature tracking. *J Cardiovasc Magn Reson* 2015; **17**: 25 [PMID: 25890093 DOI: 10.1186/s12968-015-0123-3]

19 **Taylor RJ**, Umar F, Moody WE, Meyyappan C, Stegemann B, Townend JN, Hor KN, Miszalski-Jamka T, Mazur W, Steeds RP, Leyva F. Feature-tracking cardiovascular magnetic resonance as a novel technique for the assessment of mechanical dyssynchrony. *Int J Cardiol* 2014; **175**: 120-125 [PMID: 24852836 DOI: 10.1016/j.ijcard.2014.04.268]

20 **Buss S**, Matheis P, Breuninger K, Kammerer R, Sander Y, Krautz B, Rust, L, Galuschky C, Korosoglou, G, Giannitsis E. Feature tracking in cardiac magnetic resonance imaging to evaluate normal myocardial function. *J Cardiovasc Magn Reson* 2013; **15** (Suppl 1): E51-E51 [DOI: 10.1186/1532-429X-15-S1-E51]

21 **Shang Q**, Kutty S, Danford D, Steinmetz M, Schuster A, Kuehne T, Beerbaum PB, Sarikouch S. Myocardial deformation assessed by Longitudinal Strain: chamber-specific normative data for CMR-feature tracking from the German competence network for congenital heart defects. *J Cardiovasc Magn Reson* 2015; **17** (Suppl 1): P202 [DOI: 10.1186/1532-429X-17-S1-P202]

22 **Kadiyala M**, Toole R, Bertman K, Pollack S, Reichek N. Feature Tracking: a novel method to analyze myocardial strain: Results from the CMR strain study in healthy volunteers. *J Cardiovasc Magn Reson* 2011; **13** (Suppl 1): P14-P14 [DOI: 10.1186/1532-429X-13-S1-P14]

23 **Elnakib A**, Beache GM, Sliman H, Gimel’farb G, Inanc T, El-Baz A. A novel laplace-based method to estimate the strain from cine cardiac magnetic resonance images. *In Proc IEEE Int Conf* 2013: 690-694

24 **Moore RA**, Taylor M, Mazur W, Hor KN. Assessment of strain and mechanical dyssynchrony indices in single ventricle populations by cardiac magnetic resonance feature-tracking technique. *J Cardiovasc Magn Reson* 2013; **15** (Suppl 1): E89-E89 [DOI: 10.1186/1532-429X-15-S1-E89]

25 **Kutty S**, Rangamani S, Venkataraman J, Li L, Schuster A, Fletcher SE, Danford DA, Beerbaum P. Reduced global longitudinal and radial strain with normal left ventricular ejection fraction late after effective repair of aortic coarctation: a CMR feature tracking study. *Int J Cardiovasc Imaging* 2013; **29**: 141-150 [PMID: 22581073 DOI: 10.1007/s10554-012-0061-1]

26 **Schuster A**, Kutty S, Padiyath A, Parish V, Gribben P, Danford DA, Makowski MR, Bigalke B, Beerbaum P, Nagel E. Cardiovascular magnetic resonance myocardial feature tracking detects quantitative wall motion during dobutamine stress. *J Cardiovasc Magn Reson* 2011; **13**: 58 [PMID: 21992220 DOI: 10.1186/1532-429X-13-58]

27 **Hor KN**, Baumann R, Pedrizzetti G, Tonti G, Gottliebson WM, Taylor M, Benson DW, Mazur W. Magnetic resonance derived myocardial strain assessment using feature tracking. *J Vis Exp* 2011; **(48)**: pii: 2356 [PMID: 21372778 DOI: 10.3791/2356]

28 **Schuster A**, Paul M, Bettencourt N, Morton G, Chiribiri A, Ishida M, Hussain S, Jogiya R, Kutty S, Bigalke B, Perera D, Nagel E. Cardiovascular magnetic resonance myocardial feature tracking for quantitative viability assessment in ischemic cardiomyopathy. *Int J Cardiol* 2013; **166**: 413-420 [PMID: 22130224 DOI: 10.1016/j.ijcard.2011.10.137]

29 **Ortega M**, Triedman JK, Geva T, Harrild DM. Relation of left ventricular dyssynchrony measured by cardiac magnetic resonance tissue tracking in repaired tetralogy of fallot to ventricular tachycardia and death. *Am J Cardiol* 2011; **107**: 1535-1540 [PMID: 21414597 DOI: 10.1016/j.amjcard.2011.01.032]

30 **Harrild DM**, Marcus E, Hasan B, Alexander ME, Powell AJ, Geva T, McElhinney DB. Impact of transcatheter pulmonary valve replacement on biventricular strain and synchrony assessed by cardiac magnetic resonance feature tracking. *Circ Cardiovasc Interv* 2013; **6**: 680-687 [PMID: 24300136 DOI: 10.1161/CIRCINTERVENTIONS.113.000690]

31 **Rosales XQ**, Moser SJ, Tran T, McCarthy B, Dunn N, Habib P, Simonetti OP, Mendell JR, Raman SV. Cardiovascular magnetic resonance of cardiomyopathy in limb girdle muscular dystrophy 2B and 2I. *J Cardiovasc Magn Reson* 2011; **13**: 39 [PMID: 21816046 DOI: 10.1186/1532-429X-13-39]

32 **Buss SJ**, Krautz B, Hofmann N, Sander Y, Rust L, Giusca S, Galuschky C, Seitz S, Giannitsis E, Pleger S, Raake P, Most P, Katus HA, Korosoglou G. Prediction of functional recovery by cardiac magnetic resonance feature tracking imaging in first time ST-elevation myocardial infarction. Comparison to infarct size and transmurality by late gadolinium enhancement. *Int J Cardiol* 2015; **183**: 162-170 [PMID: 25675901 DOI: 10.1016/j.ijcard.2015.01.022]

33 **Buss S**, Krautz B, Hofmann NP, Breuninger K, Sander Y, Kammerer R,Matheis P, Rust L, Galuschky C, Raake P, Pleger ST, Korosoglou G. Early assessment of infarct size by feature tracking cardiac MRI in patients with myocardial infarction. *J Cardiovasc Magn Reson* 2013; **15** (Suppl 1): P196-P196 [DOI: 10.1186/1532-429X-15-S1-P196]

34 **Breuninger K**, Lehrke S, Matheis P, Sander Y, Kammerer R, Rust L, Galuschky C, Katus HA, Korosoglou G, Buss S. Feature tracking cardiac magnetic resonance imaging for the evaluation of myocardial strain in patients with dilated cardiomyopathy and in healthy controls. *J Cardiovasc Magn Reson* 2013; **15** (Suppl 1): P167-P167 [DOI: 10.1186/1532-429X-15-S1-P167]

35 **Steinmetz M**, Alt S-C, Kutty S, Sohns JM, Unterberg-Buchwald C, Paul T, Hasenfuss G, Lotz J, Lamata P, Schuster A. Quantification of intra and inter-ventricular dyssynchrony in Ebstein's anomaly using cardiovascular magnetic resonance myocardial feature tracking. *J Cardiovasc Magn Reson* 2014; **16** (Suppl 1): O108-O108 [DOI: 10.1186/1532-429X-16-S1-O108]

36 **Smith BM**, Dorfman AL, Yu S, Russell MW, Agarwal PP, Mahani MG, Lu JC. Clinical significance of late gadolinium enhancement in patients& lt; 20 years of age with hypertrophic cardiomyopathy. *Am J Cardiol* 2014; **113**: 1234-1239 [PMID: 24513464 DOI: 10.1016/j.amjcard.2013.12.034]

37 **Thavendiranathan P**, Walls M, Giri S, Verhaert D, Rajagopalan S, Moore S, Simonetti OP, Raman SV. Improved detection of myocardial involvement in acute inflammatory cardiomyopathies using T2 mapping. *Circ Cardiovasc Imaging* 2012; **5**: 102-110 [PMID: 22038988 DOI: 10.1161/CIRCIMAGING.111.967836]

38 **Petryka J**, Quyam S, Smith B, Raphael C, Cowley B, Seale AN, Pennell D, Daubeney P, Prasad S. Prognostic significance of cardiovascular magnetic resonance feature tracking derived circumferential strain in children undergoing family screening and paediatric patients with suspected cardiomyopathy. *Am J Cardiol* 2014; **63** (12\_S): A1038 [DOI: 10.1016/S0735-1097(14)61038-X]

39 **Onishi T**, Saha SK, Ludwig DR, Onishi T, Marek JJ, Cavalcante JL, Schelbert EB, Schwartzman B, Gorcsan J. Feature tracking measurement of dyssynchrony from cardiovascular magnetic resonance cine acquisitions: comparison with echocardiographic speckle tracking. *J Cardiovasc Magn Reson* 2013; **15**: 95 [DOI: 10.1186/1532-429X-15-95]

40 **Lunning MA**, Kutty S, Rome ET, Li L, Padiyath A, Loberiza F, Bociek RG, Bierman PJ, Vose JM, Armitage JO, Porter TR. Cardiac magnetic resonance imaging for the assessment of the myocardium after doxorubicin-based chemotherapy. *Am J Clin Oncol* 2015; **38**: 377-381 [PMID: 24192805 DOI: 10.1097/COC.0b013e31829e19be]

41 **Kowallick JT**, Kutty S, Edelmann F, Chiribiri A, Villa A, Steinmetz M, Sohns JM, Staab W, Bettencourt N, Unterberg-Buchwald C, Hasenfuß G, Lotz J, Schuster A. Quantification of left atrial strain and strain rate using Cardiovascular Magnetic Resonance myocardial feature tracking: a feasibility study. *J Cardiovasc Magn Reson* 2014; **16**: 60 [PMID: 25196447 DOI: 10.1186/s12968-014-0060-6]

42 **Sado DM**, White SK, Piechnik SK, Banypersad SM, Treibel T, Captur G, Fontana M, Maestrini V, Flett AS, Robson MD, Lachmann RH, Murphy E, Mehta A, Hughes D, Neubauer S, Elliott PM, Moon JC. Identification and assessment of Anderson-Fabry disease by cardiovascular magnetic resonance noncontrast myocardial T1 mapping. *Circ Cardiovasc Imaging* 2013; **6**: 392-398 [PMID: 23564562 DOI: 10.1161/CIRCIMAGING.112.000070]

43 **Simonetti OP**, Raman SV. Straining to justify strain measurement. *JACC Cardiovasc Imaging* 2010; **3**: 152-154 [PMID: 20159641 DOI: 10.1016/j.jcmg.2009.11.005]

44 **Li W**, Liu W, Zhong J, Yu X. Early manifestation of alteration in cardiac function in dystrophin deficient mdx mouse using 3D CMR tagging. *J Cardiovasc Magn Reson* 2009; **11**: 40 [PMID: 19849858 DOI: 10.1186/1532-429X-11-40]

45 **Bratis K**, Hackmann P, Child N, Mavrogeni S, Krasemann T, Hussain T, Botnar R, Razavi R, Greil GF. CMR feature tracking in Kawasaki Disease convalescence. *J Cardiovasc Magn Reson* 2015; **17** (Suppl 1): P366-P366 [DOI: 10.1186/1532-429X-17-S1-P366]

**P-Reviewer:** Fett JD, Rauch B, Ueda H **S-Editor:** Ji FF **L-Editor: E-Editor:**

**Table 1 Validation studies at glance**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Ref. |  Technique compared | Cardiac disease | Population studied (*n*) | Results of validation |
| Taylor *et al*[19] | - | Healthy individuals | 55 | FT is highly reproducible within operators, requiring a short analysis time |
| Augustine *et al*[4] | Myocardial tagging | Healthy individuals | 145 | FT measurements of circumferential strain showed reasonable agreement with myocardial tagging |
| Schuster *et al*[2] | - | Healthy individuals | 20  | FT showing reasonable intra-observer reproducibility in different groups of individuals |
| Lu *et al*[5] | HAARP | Anthracycline induced cardiomyopathy | 26 | Circumferential strain was found to be a robust and reproducible index of myocardial deformation |
| Hor *et al*[7] | HAARP | Duchenne Muscular Dystrophy | 233 | Good correlation between CMR-FT and HAARP for the mean circumferential strain values |
| Morton *et al*[8] | - | Healthy individuals | 16 | FT had good inter-study reproducibility for global strain analysis |
| Kempny *et al*[9] | STE and simple EBD | ToF | 25 | Feature tracking showed better inter observer reproducibility for circumferential or radial left ventricular and longitudinal right ventricular global strain when compared to STE |
| Padiyath *et al*[10] | 2D echocardiography | 20 patients with ToF and 20 healthy controls | 40 | Reasonable agreement between FT and 2D echo in measurement of global circumferential strain and global longitudinal strain for the left ventricle |
| Harrild *et al*[12] | Myocardial tagging | HCM | 24 | Closer agreement between 2 modalities in measuring time to peak strain |
| Orwat *et al*[13] | Trans-thoracic echocardiogram with speckle tracking.  | HCM  | 40 | Trans-thoracic echocardiogram with speckle tracking. They found decent agreement between left ventricular longitudinal strain measurements between the 2 modalities while the agreement for circumferential strain not encouraging |

HCM: Hypertrophic cardiomyopathy; EBD: Endocardial border delineation; STE: Speckle tracking echocardiography; ToF: Teratology of Fallot; HAARP: Harmonic phase imaging analysis; CMR-FT: Cardiac magnetic resonance feature tracking.

**Table 2 Feature tracking algorithm**

|  |  |
| --- | --- |
| Algorithm | Strain estimation algorithm |
| Step 1 | **Wall borders segmentation**Segment the LV wall from cine CMR |
| Step 2 | **For each image, find the centerline of the LV wall as follows**Start with the inner border of the LV wall Solve the Laplace equation between the inner and outer wall borders to find the corresponding outer points to the defined inner points in step 2(a) Pick the points located equidistant from the corresponding point-pairs Form the centerline (*i.e*., mid-wall border) using a closed spline fit for the selected points |
| Step 3 | **Tracking**For each two successive images, solve the Laplace equation between their respective inner borders, mid-walls, and outer bordersTrack the co-allocated points at the inner, mid-wall, and outer edges of the first image frame (defined in step 2) throughout the cardiac cycle |
| Step 4 | **Strain estimation**Estimate the circumferential strains by tracking the change in distance between tracked points on the same border (*i.e.*, inner, mid-wall, and outer borders)Estimate the radial strains by tracking the change in distance between radially oriented tracked points |

CMR: Cardiac magnetic resonance imaging.