Echocardiographic Assessment of Myocardial Strain

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Echocardiographic strain imaging, also known as deformation imaging, has been developed as a means to objectively quantify regional myocardial function. First introduced as post-processing of tissue Doppler imaging velocity converted to strain and strain rate, strain imaging has more recently also been derived from digital speckle tracking analysis. Strain imaging has been used to gain greater understanding into the pathophysiology of cardiac ischemia and infarction, primary diseases of the myocardium, and the effects of valvular disease on myocardial function, and to advance our understanding of diastolic function. Strain imaging has also been used to quantify abnormalities in the timing of mechanical activation for heart failure patients undergoing cardiac resynchronization pacing therapy. Further advances, such as 3-dimensional speckle tracking strain imaging, have emerged to provide even greater insight. Strain imaging has become established as a robust research tool and has great potential to play many roles in routine clinical practice to advance the care of the cardiovascular patient. This perspective reviews the physiology of myocardial strain, the technical features of strain imaging using tissue Doppler imaging and speckle tracking, their strengths and weaknesses, and the state-of-the-art present and potential future clinical applications. (J Am Coll Cardiol 2011;58:1401–13) © 2011 by the American College of Cardiology Foundation

Noninvasive assessment of regional myocardial function is important to the field of cardiovascular medicine to diagnose disease, assess therapeutic interventions, and predict clinical outcomes. Although magnetic resonance imaging and computed tomography imaging are useful diagnostic alternatives, echocardiography remains advantageous for widespread clinical use because of its portability, low risk, and comparatively high temporal resolution. Echocardiographic strain imaging, also known as deformation imaging, is a technological advancement that has been developed as a means to objectively quantify regional myocardial function (1–3). First introduced as a post-processing feature of tissue Doppler imaging (TDI) with velocity data converted to strain and strain rate, strain imaging information has more recently also been derived from speckle tracking computer processing (4,5). Currently, most echocardiography laboratories continue to use the subjective visual assessment of wall motion for resting and stress imaging for everyday clinical use, and strain imaging has been more often regarded as a research tool. Adoption of strain imaging in clinical practice appears to have been gaining momentum more recently. This paper reviews the physiology of myocardial strain, the technical features of strain imaging using both TDI and speckle tracking, their strengths and weaknesses, and the potential present and future clinical applications.

Physiology of Left Ventricular Strain

D’Hooge et al. (2), Dandel and Hetzer (6), and Mor-Avi et al. (7) published scholarly reviews of the technical features of strain imaging in detail previously. Briefly, myocardial regional mechanics assessed by echocardiographic approaches have been described by 4 principal types of strain or deformation: longitudinal, radial, circumferential, and rotational (Fig. 1). Although myocardial fiber orientation results in these strain vectors occurring 3 dimensionally in an integrated manner, most investigative works have been done using individual strain assessments. The term strain applied to echocardiography in a simplistic sense is to describe lengthening, shortening, or thickening, also known as regional deformation. Strain may be \( \varepsilon = \Delta L/L_0 \) understood as an example of an infinitesimally thin bar where the only possible deformation is lengthening or shortening. Accordingly linear strain or the amount of deformation can be defined by the change in length divided by the original length expressed by the formula: \( \varepsilon = \Delta L/L_0 \), where \( \varepsilon \) = strain, \( \Delta L \) = change in length, and \( L_0 \) = original length. In reality, the myocardial wall as a 3-dimensional (3D) object has strain that may occur along 3 planes (x-, y-, and z-axes), known as normal strains, and 6 shear strains (2,3,6). Despite the complexities of myocardial wall dynamics, some meaningful information has been derived using the simplified linear strain or deformation model by echocardiography.

Strain by TDI

The first description of echocardiographic strain was derived from TDI velocity data using the Doppler equation to convert ultrasound frequency shifts to velocity information

From the University of Pittsburgh, Pittsburgh, Pennsylvania. Dr. Gorcsan has received research grant support from GE and Toshiba. Dr. Tanaka has reported that he has no relationships relevant to the contents of this paper to disclose.

Manuscript received August 8, 2010; revised manuscript received May 31, 2011, accepted June 10, 2011.
along the scan lines. Because the fundamental data produced by TDI were velocity information, strain rate (strain per unit of time) was derived from the velocity data using the equation: 
\[ \varepsilon = \frac{V_1 - V_2}{L} \]
where \( \varepsilon \) = strain rate, \( V_1 \) = velocity at point 1, \( V_2 \) = velocity at point 2, and \( L \) = length, usually set at 10 mm. Strain rate and strain data using TDI required the direction of the myocardial wall motion to be along the ultrasound scan line (11). Longitudinal shortening using the apical windows was often used because of the favorable Doppler angle of incidence (3) (Fig. 2). The alternative was from the parasternal views where the relative transmural change in velocity could be calculated as the velocity gradient, similar to strain rate (e.g., in the posterior wall) (8–10). TDI strain rate data could be integrated over time to determine strain (Fig. 3). Because all TDI information is affected by the Doppler angle of incidence, Doppler angle correction analysis programs were developed to determine wall motion for regions where the motion was not aligned with the Doppler scan line (11). However, it remained impossible to assess wall motion by TDI when the angle of motion was close to 90°. Accordingly, the majority of the published literature on echocardiographic strain imaging using TDI assessed longitudinal strain from the apical windows with left ventricular (LV) shortening and lengthening aligned with the Doppler scan lines. The important technical features of TDI acquisition and analysis appear in the Online Appendix.

**Strain by Speckle Tracking**

A more recent echocardiographic approach to strain analysis is speckle tracking. Speckle tracking is a post-processing computer algorithm that uses the routine grayscale digital images. Although several manufacturers have devised speckle tracking echocardiographic approaches, the fundamental approach is similar (4,12,13). Briefly, routine grayscale digital images of the myocardium contain unique speckle patterns. A user-defined region of interest is placed on the myocardial wall. Within this region of interest, the image-processing algorithm automatically subdivides regions into blocks of pixels tracking stable patterns of speckles. Subsequent frames are then automatically analyzed by searching for the new location of the speckle patterns within each of the blocks using correlation criteria and the sum of absolute differences (Fig. 4). The location shift of these acoustic markers from frame to frame representing tissue movement provides the spatial and temporal data used to calculate velocity vectors. Temporal alterations in these stable speckle patterns are identified as moving farther apart or closer together and create a series of regional strain vectors. Because strain information is not dependent on the Doppler angle of incidence like TDI strain, several more strain analyses are possible, including longitudinal, circumferential, radial, and rotational. Additional technical features of speckle tracking acquisition and analysis appear in the Online Appendix.

**Strain Imaging for Myocardial Ischemia and Viability**

Significant insights pertaining to the pathophysiology of ischemic heart disease have resulted from echocardiographic strain imaging over the past decade (14–18). Previously, the clinical assessment of wall motion abnormalities at rest or with stress by exercise or dobutamine has consisted of visual assessment of endocardial excursion and wall thickening. The addition of strain imaging has refined the ability of echocardiography to detect and objectively qualify specific patterns of ischemia and infarction. Because ischemic wall motion abnormalities are often associated with passive motion, such as passive expansion and recoil and tethering from adjacent segments, strain imaging has the advantage of differentiating active contraction from passive motion, which often is difficult visually (19). Strain imaging has been validated in animal models of acute ischemia and infarction (20,21) (Fig. 5). Edvardsen et al. (16) used TDI longitudinal strain in humans to demonstrate patterns of LV wall lengthening with acute ischemia while patients underwent occlusion of the left anterior descending coronary artery (16). Specifically, strain quantified expansion in the apical septal segments (7.5 ± 6.5% vs. −17.7 ± 7.2%,...
p < 0.001) and reduced compression in the mid-septal segments. Skulstad et al. (19) used radial and longitudinal strain imaging to define the pattern of post-systolic shortening with acute coronary occlusion in an animal model with sonomicronometry validation. Kukulski et al. (22) extended the concept of post-systolic shortening using TDI strain in humans undergoing coronary angioplasty with peak strain occurring after aortic valve closure and restoration of strain after reperfusion (Fig. 6). Weidemann et al. (18) proposed a post-systolic strain index as being predictive of the extent of transmurality of myocardial infarction. Lim et al. (23) subsequently showed that time-to-peak TDI strain was significantly correlated with the percentage of infarct transmurality with a modest correlation coefficient of \( r = 0.69 \).

An important contribution of strain imaging has been as an adjunct to low-dose dobutamine stress echocardiography (DSE) to assess myocardial viability. Hanekom et al. (24) examined 55 patients with ischemic heart disease by DSE with both visual wall motion assessment and longitudinal strain and strain rate imaging followed by revascularization by coronary bypass or percutaneous interventions. Patients were re-examined 9 months later to determine LV functional recovery after revascularization as evidence of viability. Visual wall motion assessment alone had a sensitivity of 71% and a specificity of 77% for detecting viable segments by DSE. Sensitivity was modestly but significantly improved by longitudinal strain and strain rate imaging, with the most favorable results achieved by a combination of visual assessment and strain imaging with a sensitivity 84% and a specificity of 80%.

Although radionuclide single-photon emission computed tomography imaging or gadolinium-enhanced cardiac magnetic resonance (CMR) imaging appear to be preferred currently to quantify myocardial scar, strain imaging continues to emerge as a new potential approach (25,26). Roes et al. (27,28) used speckle tracking longitudinal strain to assess viable myocardium compared with contrast-enhanced CMR imaging in 90 patients with chronic ischemic LV dysfunction. A favorable correlation was found between resting longitudinal LV strain and the extent of scarring by CMR imaging. The mean longitudinal strain in segments without scarring was \(-10.4 \pm 5.2\%\) compared with \(0.6 \pm 4.9\%\) in segments with transmural scarring (\( p < 0.001 \)). A strain cutoff value of \(-4.5\%\) had a sensitivity of 81.2% and a specificity of 81.6% for predicting viable myocardium from segments with transmural scarring by contrast-enhanced CMR imaging. Bansal et al. (29) compared speckle tracking longitudinal strain with TDI of strain during low-dose DSE to determine viability in 55 patients with subsequent revascularization. They reported TDI of strain to be more accurate to determine viability than speckle tracking longitudinal strain. The precise reason for this difference is unknown; however, the lower temporal resolution of speckle tracking strain compared with TDI of strain is a potential factor. Future refinements of speckle tracking for patients with ischemic heart disease are likely forthcoming.

**Applications of Strain Imaging for Cardiac Resynchronization Therapy**

Strain imaging by both TDI and speckle tracking approaches have been reported to assess abnormal regional
mechanical activation patterns, known as dyssynchrony, with particular interest for patients undergoing cardiac resynchronization therapy (CRT). Interest has focused on dyssynchrony as a means to predict response to CRT because approximately one-third of patients do not appear to benefit using standard clinical selection criteria (30,31). LV longitudinal shortening velocities by TDI from the apical views have been introduced as a means to quantify LV dyssynchrony (32–34). The 2 most popular applications of TDI velocities have included the differences in timing of peak velocity between LV walls (opposing wall delay) and the SD in time to peak velocities from 12 sites (Yu Index) (32–35). The advantage of TDI velocities is that the signal-to-noise ratio is high, but a major limitation is the inability of velocity to differentiate active from passive motion. The multicenter PROSPECT (Providing Regional Observations to Study Predictors of Events in the Coronary Tree) study suggested that the TDI opposing wall delay performed relatively better than other dyssynchrony indexes for predicting LV reverse remodeling; however, echocardiographic dyssynchrony was not considered reliable enough to replace current selection criteria for CRT (36). Accordingly, interest in the quantification of LV dyssynchrony by strain imaging has continued. Yu et al. (35) observed that the 12-segment SD of time-to-peak TDI velocities was superior to TDI strain for predicting LV reverse remodeling after CRT in 256 patients. On the other hand, Miyazaki et al. (37) showed contrary findings that TDI of longitudinal strain might be a preferred dyssynchrony technique to longitudinal velocities. In their study of 120 heterogeneous subjects including normal subjects and patients with left bundle branch block (LBBB) and reduced ejection fraction (EF). They observed considerable overlap of TDI velocities between groups and difficulties with analysis of multiple velocity spikes even in normal subjects. In contrast, they believed that longitudinal strain more reliably distinguished patients with LBBB or decreased EF from those with normal EF and normal QRS duration. However, TDI of longitudinal strain is severely affected by the Doppler angle of incidence, which is a limitation for enlarged spherical left ventricles, commonly encountered in the CRT patients. We showed more recently in a prospective study of 229 CRT patients that a TDI velocity opposing wall delay of ≥80 ms and Yu Index ≥32 ms were significantly associated with long-term survival over a 4-year period (38).

Specific Speckle Tracking Applications of Strain for Dyssynchrony

Four different speckle tracking dyssynchrony approaches have been suggested, including radial strain (myocardial thickening) and circumferential strain (myocardial shortening) assessed from short-axis views (Figs. 7 and 8) and longitudinal strains (myocardial shortening) and trans-
verse (myocardial thickening) assessed from apical views (Figs. 9 and 10). Radial and transverse strains have positive curves, reflecting myocardial thickening. Conversely, longitudinal and circumferential strains have negative curves, reflecting myocardial shortening. Dysynchrony is typically characterized in LBBB by early septal radial thickening, followed by delayed posterior and lateral wall thickening. Suffoletto et al. (13) first reported the utility of speckle tracking radial strain in quantifying dyssynchrony, defined as the time difference in peak anteroseptum to posterior wall strain $\geq$130 ms, to be associated with EF response to CRT. A combined
approach of using both TDI longitudinal velocity opposing wall delay and speckle tracking radial strain was shown to be of additive value for predicting response to CRT (39). Lim et al. (40) reported the strain delay index determined by longitudinal speckle tracking strain from standard apical views was a marker of both LV dyssynchrony and myocardial contractility. They demonstrated that the strain delay index ≥25% strongly predicted response to CRT with a 95% sensitivity and an 83% specificity and correlated with reverse remodeling in both the ischemic (r = 0.68) and nonischemic (r = 0.68) patients (p < 0.0001 for both). The STAR (Speckle Tracking and Resynchronization) study was the first prospective multicenter study to associate speckle tracking strain dyssynchrony with EF response and long-term survival after CRT (41). Speckle tracking radial strain from short-axis views and transverse strain from apical views were associated with response to CRT in 132 patients, whereas longitudinal and circumferential strain appeared less sensitive in detecting important dyssyn-
chrony. A lack of dyssynchrony before CRT by radial or transverse strain (or both) was significantly associated with death, heart transplantation, or LV assist device implantation. Dyssynchrony by speckle tracking radial strain was shown to be strongly associated with long-term survival after CRT in another study of 229 patients. A lack of radial dyssynchrony was particularly associated with an unfavorable outcome in those with a shorter QRS duration of 120 to 150 ms. Most recently, Delgado et al. (26) showed an association of a lack of dyssynchrony by speckle tracking radial strain with death or heart failure hospitalization in a series of 397 CRT patients with ischemic heart disease. Similar results for dyssynchrony analysis using speckle tracking radial strain may be achieved using different software approaches, and it appears promising as an adjunct for patient selection for CRT with borderline QRS duration (42,43).

### 3D Speckle Tracking Strain

A newer speckle tracking approach to quantify LV dyssynchrony is 3D speckle tracking echocardiography (44,45). 3D speckle tracking provides a more comprehensive evaluation of LV mechanics from pyramidal 3D datasets than was previously possible. 3D cine loops of regional strain are color coded and divided into 16 segments for time-strain curves, polar maps, and 3D displays (Fig. 11). Maximum opposing wall delay and SD by 3D speckle tracking strain significantly correlated with similar 2-dimensional (2D) strain measures, with 3D having the advantage of more precise mechanical
activation mapping to assist with LV lead positioning (45) (Fig. 12). 3D speckle tracking strain was also useful for showing differences in the sites of earliest activation in right ventricle–paced patients compared with those with LBBB, but similar sites of latest activation and similar response to CRT (44). Future advancements with expansion of applications for 3D speckle tracking are anticipated.

Assessment of Rotational Strain

Notomi et al. (12,46) used TDI and speckle tracking strain methods to assess LV rotational mechanics and calculate torsion. They elegantly reported the normal pattern of slight clockwise basal rotation and greater counterclockwise apical rotation as viewed in the standard short-axis echocardiographic view orientation (Fig. 13).

The combination of these rotational strain vectors was described as torsion. They validated rotational and torsion measures against tagged cine magnetic resonance imaging using TDI during systole and early diastole (apical and basal rotation, \( r = 0.87 \) and 0.90, respectively; for torsion, 0.84; \( p < 0.0001 \)). In a second related study, they performed similar comparisons using speckle tracking measures of rotation and torsion in 13 patients also demonstrating a strong correlation with tagged magnetic resonance imaging (\( y = 0.95x + 0.19, r = 0.93, p < 0.0001 \)). This group went on to describe a temporal link between LV untwisting, relaxation, and suction in an animal model, showing that the peak untwisting rate was an independent predictor of tau and intraventricular pressure gradient (\( p < 0.0001 \) for both) (47–49). Tan et
al. (50) reported on the role of LV untwisting in patients with heart failure and normal EF, observing reduced and delayed diastolic untwisting resulting in reduced LV suction at rest and on exercise. Bertini et al. (51) demonstrated reduced subendocardial LV twist in patients with ST-segment elevation myocardial infarction, and Andrade et al. (52) recently applied 3D speckle tracking to assess LV twist.

### Applications of Strain Imaging for Cardiomyopathies

TDI and speckle tracking strain have been used to characterize patients with primary myocardial diseases including hypertrophic cardiomyopathy, cardiac amyloidosis, drug-induced cardiomyopathy, and arrhythmogenic right ventricular dysplasia (9,53–58). Palka et al. (9) demonstrated that early diastolic strain rates were significantly lower in patients with hypertrophic cardiomyopathy compared with patients with hypertrophy related to hypertension or those with athlete's heart. Kato et al. (56) more recently found that TDI of longitudinal strain of <10.6% (average of the anterior, inferior, septal, and lateral) was associated with a sensitivity of 85% and a specificity of 100% for the detection of hypertrophic cardiomyopathy. Furthermore, Yang et al. (57) reported unique findings that longitudinal strain by TDI was significantly lower in the mid-septum than that of the apical and basal segments in patients with hypertrophic cardiomyopathy (p < 0.01), and 55% of patients had a positive peak strain value (paradoxical systolic expansion). Yajima et al. (59) recently reported regional peak longitudinal speckle tracking strain can distinguish fibrotic from nonfibrotic lesions in LV myocardium in patients with hypertrophic cardiomyopathy and normal LV myocardium in healthy controls.

Koyama et al. (53) first demonstrated the incremental value of longitudinal strain and strain rate for the diagnosis of cardiac amyloidosis. They proposed that

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**Figure 10** Transverse Strain by 2D Speckle Tracking in a Normal Subject and a Heart Failure Patient With LBBB

(A) An example of speckle tracking transverse (Trans.) strain using the apical 4-chamber view in a normal subject demonstrating synchronous peak transverse strain curves (arrow). (B) An example of speckle tracking transverse strain using the apical 4-chamber view in a heart failure patient with LBBB referred for resynchronization therapy demonstrating early septal peak strain followed by late lateral wall peak strain, resulting in dyssynchrony (arrow). Abbreviations as in Figure 7.
longitudinal strain imaging could identify a group of patients with probable subclinical cardiac amyloidosis earlier in the course of the disease process at a time when routine 2D echocardiography and Doppler assessment of diastolic function was normal. In 119 patients with cardiac amyloidosis, they reported a basal longitudinal strain value of less than −12.0% was predicted of cardiac death over a year (60). They concluded that strain and strain rate displayed greater sensitivity than velocity or displacement for detecting subtle abnormalities in the longitudinal contraction early in the patient’s course with amyloidosis. Bellavia et al. (55) also reported similar findings from 103 patients with biopsy-proven cardiac amyloidosis.

Detection of chemotherapeutic cardiac toxicity is of great clinical importance. Ho et al. (54) reported the long-term effects of standard chemotherapy including trastuzumab on myocardial function in asymptomatic breast cancer survivors using 2D speckle tracking strain. They found that the chemotherapy group had reduced global longitudinal speckle tracking strain in comparison with normal controls (−18.1 ± 2.2% vs. −19.6 ± 1.8%, p = 0.0001), even though the EF was similar (62 ± 4% vs. 60 ± 3%). In contrast, global radial speckle tracking strain did not differ significantly between the 2 groups. Prakasa et al. (58) evaluated the utility of TDI of longitudinal strain in patients with arrhythmogenic right ventricular dysplasia to determine whether these modalities could provide complementary and incremental diagnostic information. They found that a value of −18% of right ventricular free wall longitudinal strain provided the greatest discriminatory power for differentiating patients with arrhythmogenic right ventricular dysplasia from normal controls. Importantly, 4 patients had a diagnosis of arrhythmogenic right ventricular dysplasia by TDI of strain with morphologically normal right ventricles by 2D echocardiography.

Applications of Strain Imaging for Effects of Valvular Heart Disease

The chronic effects of abnormal loading from valvular disease on myocardial function may be difficult to detect by conventional means, and strain imaging may play a role (61–67). Delgado et al. (62) demonstrated that patients with severe aortic stenosis and preserved EF exhibited decreased radial, circumferential, and longitudinal speckle tracking strain. In addition, significant improvement in these parameters was observed at long-term follow-up after aortic valve replacement, whereas EF remained unchanged. de Isla et al. (63) reported that preoperative speckle tracking longitudinal strain at the level of the interventricular septum from the apical 4-chamber view strongly predicted a post-operative EF decrease of >10% in patients with chronic severe mitral regurgitation. Tayyareci et al. (64) demonstrated that longitudinal and circumferential strains assessed by velocity vector imaging were significantly decreased in asymptomatic patients with severe aortic regurgitation and normal EF compared with normal volunteers. Furthermore, Onishi et al. (61) recently reported that preoperative systolic radial strain rate derived from TDI was the best predictor of post-operative LV systolic dysfunction of an EF <50% in patients with severe aortic regurgitation and a normal EF. These findings highlight that TDI of or 2D speckle tracking strain enables an early detection of subtle changes in LV systolic function in patients with valvular heart disease.

Conclusions

Echocardiographic strain imaging, also known as deformation imaging, has provided a means to objectively
quantify myocardial mechanical function. Originally introduced as a product of TDI, speckle tracking is a more recent extension of strain imaging. Strain imaging has provided greater understanding of the pathophysiology of cardiac ischemia and infarction, primary diseases of the myocardium, assessment of dyssynchrony for CRT, the effects of valvular disease on myocardial function, and the mechanics of diastolic function. Strain by 3D speckle tracking has emerged as a further advance to provide even greater insight. Strain imaging has become established as
REFERENCES


Key Words: deformation • echocardiography • myocardial.

APPENDIX

For additional technical features of TDI and speckle tracking acquisition, please see the online version of this article.