Assessment of Myocardial Mechanics Using Speckle Tracking Echocardiography: Fundamentals and Clinical Applications

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The authors summarize the recent developments in speckle-tracking echocardiography (STE), a relatively new technique that can be used in conjunction with two-dimensional or three-dimensional echocardiography for resolving the multidirectional components of left ventricular (LV) deformation. The tracking system is based on grayscale B-mode images and is obtained by automatic measurement of the distance between 2 pixels of an LV segment during the cardiac cycle, independent of the angle of insonation. The integration of STE with real-time cardiac ultrasound imaging overcomes some of the limitations of previous work in the field and has the potential to provide a unified framework to more accurately quantify the regional and global function of the left ventricle. STE holds promise to reduce interobserver and intraobserver variability in assessing regional LV function and to improve patient care while reducing health care costs through the early identification of subclinical disease. Following a brief overview of the approach, the authors pool the initial observations from clinical studies on the development, validation, merits, and limitations of STE. (J Am Soc Echocardiogr 2010;23:351-69.)

Keywords: Speckle tracking, Velocity Vector Imaging, Left ventricular deformation, Strain

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Target Audience:
This activity is designed for all cardiovascular physicians and cardiac sonographers with a primary interest and knowledge base in the field of echocardiography: in addition, residents, researchers, clinicians, intensivists, and other medical professionals with a specific interest in cardiac ultrasound will find this activity beneficial.
Objectives:
Upon completing the reading of this article, the participants will better be able to:

1. Define the terms strain and strain rate as they relate to left ventricular (LV) myocardial function.
2. Describe how speckle tracking echocardiography is used to determine strain and strain rate.
3. Name the advantages and disadvantages of tissue Doppler-derived strain and strain rate imaging compared to speckle tracking echocardiography (STE) derived strain and strain rate.
4. Recognize the different directions of normal and shear strain and how shear strain relates to torsion.
5. Identify the clinical applications of STE for assessment of LV deformation.

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Tissue Doppler–derived strain and strain rate imaging were introduced several years ago as a method to quantify myocardial mechanical function.[1] However, tissue Doppler–derived strain variables faced a number of criticisms, particularly in relation to angle dependency, noise interference, and substantial intraobserver and interobserver variability.[2] Speckle-tracking echocardiography (STE) has emerged as an alternative technique that analyzes motion by tracking natural acoustic reflections and interference patterns within an ultrasonic window. The image-processing algorithm tracks user-defined regions of interest which are comprised of blocks of approximately 20 to 40 pixels containing stable patterns that are described as "speckles", "markers", "patterns", "features", or "fingerprints".[3-6] Speckles are tracked consecutively frame to frame using a sum–of–absolute differences algorithm to resolve angle-independent two-dimensional (2D) and three-dimensional (3D) sequences of tissue motion and deformation. Data regarding the accuracy, validity, and clinical application of speckle-tracking imaging are rapidly accumulating. In this review, we summarize the current trends in the quantitative assessment of cardiac

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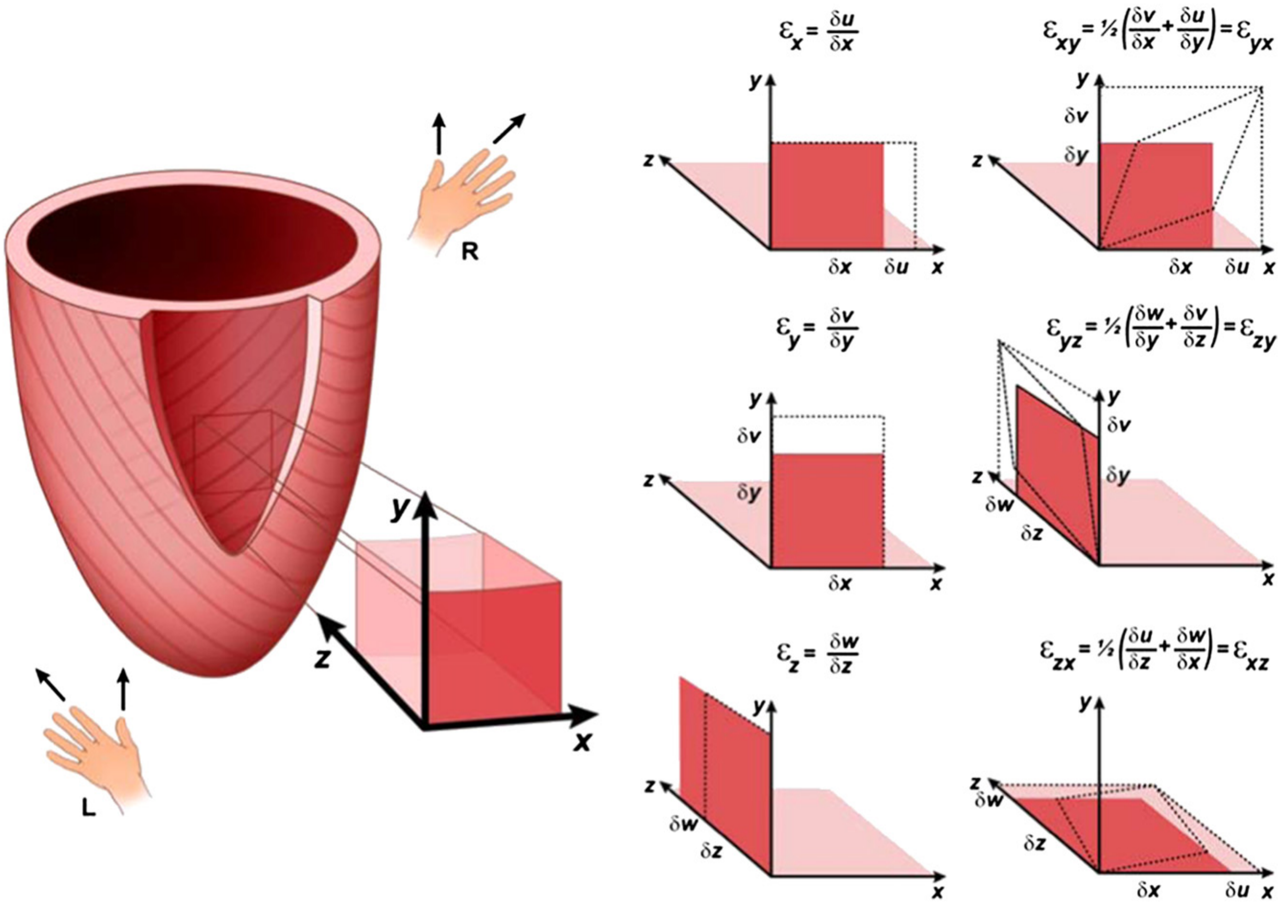

Figure 1 Linking the myofiber architecture and 3-directional deformation of the left ventricle. The *left panel* shows a schematic representation of the myocardial fiber orientation in the left ventricle that changes continuously from a right-handed helix (R) in the subendocardial region to a left-handed helix (L) in the subepicardial region, as seen over the anterior wall of the left ventricle. The *panels in the center and to the left* show the normal (ϵ_x, ϵ_y, and ϵ_z), and 3 components of shear strain (ϵ_{xy}, ϵ_{xz}, and ϵ_{yz}) in a block of myocardial tissue in which the *x*-axis is oriented at a tangent to the circumferential direction, the *y*-axis is oriented longitudinally, and the *z*-axis corresponds to the radial direction of the left ventricle, with *u*, *v*, and *w* representing displacements in the *x*, *y*, and *z* directions, respectively. Shear strain can be defined exactly the same way as normal strain: the ratio of deformation to original dimensions. In the case of shear strain, however, it is the amount of deformation perpendicular to a given line rather than parallel to it. For example the shear strain ϵ_{xy} is the average of the shear strain on the *x* face along the *y* direction and on the *y* face along the *x* direction.

deformation, highlighting the transition from Doppler tissue imaging (DTI) toward STE. First, a brief theoretical basis of applications in myocardial strain imaging is presented, followed by an in-depth review of evolving applications in different clinical situations.

MYOCARDIAL STRAIN IMAGING

Regional strain is a dimensionless measurement of deformation, expressed as a fractional or percentage change from an object's original dimension.[7] Strain rate, on the other hand, refers to the speed at which deformation (ie, strain) occurs. As a spatial derivative of velocity, strain rate provides increased spatial resolution for precise localization of diseased segments. However, strain rate needs high temporal resolution (>100 Hz) to avoid underestimation due to undersampling. Therefore, Doppler, because of its high temporal resolution, is superior to speckle tracking for strain rate imaging. However, Doppler-derived strain is angle dependent and highly susceptible to noise arising from the blood pool, aliasing and reverberation. The use of integrated strain helps reduce random noise while maintaining near similar spatial information.

The amount of shortening or stretch in the tissue or fibers describes the normal strain, and the amount of distortion associated with the sliding of plane layers over each other describes the shear strain within a deforming body (Figure 1). There are two methods for assessing deformation on a continuum. One description is made in terms of the material coordinates. This is called "material description" or "Lagrangian description," which defines motion around a given point in tissue as it traverses through space and time. Similar to tagged magnetic resonance imaging (MRI), speckle-tracking technology analyzes Lagrangian strain, in which the end-diastolic tissue dimension represents the unstressed, initial material length as a fixed reference throughout the cardiac cycle.[8] An alternative way to describe deformation is to consider the relative velocity of motion at a particular location in space as a function of time, referencing the region in terms of the spatial coordinates. This is also called the "spatial description" or "Eulerian description." DTI analyzes Eulerian strain, which is derived from the temporal integral of the DTI strain rate signal and uses instantaneous lengths for the reference length.[9] In practice, tissue Doppler scanners can convert Eulerian strain into Lagrangian strain. Likewise, by taking the inverse integral of Lagrangian strain, one may also calculate Eulerian strain.[9]

The general state of strain at a point in a body is composed of 3 components of normal strain (ϵ_x, ϵ_y, and ϵ_z), and 3 components of shear strain (ϵ_{xy}, ϵ_{xz}, and ϵ_{yz}). Therefore, for the left ventricle, 3 normal strains (longitudinal, circumferential, and radial) and 3 shear strains (circumferential-longitudinal, circumferential-radial, and longitudinal-radial) are used to describe left ventricular (LV) deformation in 3 dimensions (Figure 1). One of the principal purposes of LV shearing deformation lies in amplifying the 15% shortening of myocytes into 40% radial LV wall thickening, which in turn results in a >60% change in LV ejection fraction in a normal heart.[10] Because the degree of shearing increases toward the subendocardium, higher strains are seen at the subendocardium resulting in a subepicardial-to-subendocardial thickening strain gradient.

Myocardial shear in the circumferential-longitudinal plane results in twist or torsional deformation of the LV during ejection such that, when viewed from the apex, the LV apex rotates in a clockwise direction and the base rotates in a counterclockwise direction.[11] Terms such as *rotation*, *twist*, and *torsion* are often used interchangeably for explaining the circumferential-longitudinal shear deformation of the left ventricle. For a uniform description, we emphasize that the term *rotation* should refer to the rotation of short-axis sections of the left ventricle as viewed from the apical end and defined as the angle (in degrees or radians) between radial lines connecting the center of mass of that specific cross-sectional plane to a specific point in the myocardial wall at end-diastole and at any other time during systole.[11] The term *torsion* should be used for defining the base-to-apex gradient in the rotation angle along the longitudinal axis of the left ventricle, expressed in degrees per centimeter or radians per meter.[11] The absolute apex-to-base difference in LV rotation (also in degrees or radians) is stated as the net LV twist angle or the net LV torsion angle.[11] It must be emphasized that LV length and diameter change dynamically during a cardiac cycle, and therefore these normalization schemes permit comparison of only the peak magnitude of torsion for different sizes of the left ventricle. LV torsion during ejection results in storage of potential energy into the deformed myofibers and myocardial matrix. With the onset of relaxation, the stored energy is released back, like a spring uncoiling, generating suction and forces for rapid early diastolic restoration. Myocardial deformation is thus of functional interest during both systole and diastole.

Myocardial deformation during ejection demonstrates extensive transmural tethering such that subendocardial and subepicardial regions undergo simultaneous shortening along the fiber and cross-fiber direction during ejection.[11] Subendocardial strains are higher in magnitude than subepicardial strains. Within the subendocardium, the magnitude of circumferential strains during ejection exceeds that of longitudinal strains.

VALIDATION OF SPECKLE-TRACKING ECHOCARDIOGRAPHY

Speckle tracking requires a thorough understanding of echocardiographic imaging technique for both image acquisition and myocardial border tracing. In addition, images must be of high-resolution quality to track regions of interest accurately. Myocardial strain derived from STE has been validated using sonomicrometry[12-14] and tagged MRI.[1,12,15-17] Speckle-tracking strain results correlate significantly with tissue Doppler–derived measurements. Tissue Doppler technology is dependent on achieving a parallel orientation between the ultrasound beam and the direction of motion and therefore is applied mostly in apical views for recording longitudinal strains and from midanterior and midinferior segments of the left ventricle in short-axis views for recording radial strains. STE, in contrast, can analyze the longitudinal and radial deformation of all LV segments from apical views and radial and circumferential strain of all LV segments from the short-axis views. In comparison with DTI, receiver operating characteristic curve analysis has shown that longitudinal and radial strain measured using STE has a significantly greater area under the curve than DTI strain in differentiating normal and dysfunctional segments.[17]

Speckle tracking–derived strain and strain rates do not require scaling for any index of LV morphology.[18] Overall, speckle tracking appears to be highly reproducible and minimally affected by intraobserver and interobserver variability.[19] However, some studies have suggested underestimation of longitudinal strain with STE.[20] Variations between MRI tagging and STE may be secondary to misaligned image planes and out-of-plane motion, which may not be accounted for by STE. Furthermore, initial studies using contrast echocardiography have shown wide interindividual variability in the precision of strain quantification, suggesting that additional investigations are needed to understand thoroughly the use of strain techniques concomitant with contrast echocardiography.[21]

Application of STE has also been extended for studying regional and global function of other cardiac chambers including the right ventricle and the left atrium. The complex geometry and thin walls of the right ventricle and left atrium may present considerable challenges in optimal positioning of the region of interest. Investigations with STE thus far have primarily attempted to define the longitudinal deformation of the right ventricle,[22-28] with some preliminary data suggesting a potential role in measuring the circumferential and rotational deformation of the right ventricle.[29] For the left atrium, DTI-derived deformation analyses have generally been restricted to the annular region and the midsegments of the left atrium.[30-32] STE may have potential advantages in assessing deformation from all segments of the left atrium.[33] Further studies are needed to understand the incremental value and potential impact of these applications in clinical settings.

CLINICAL APPLICATIONS OF SPECKLE-TRACKING ECHOCARDIOGRAPHY FOR ASSESSMENT OF LEFT VENTRICULAR DEFORMATION

Table 1 presents a general classification scheme that may be helpful for the application of STE-derived multidirectional strains in clinical practice.[34] In general, longitudinal LV mechanics, which are predominantly governed by the subendocardial region, are the most vulnerable component of LV mechanics and therefore most sensitive to the presence of myocardial disease. The midmyocardial and epicardial function may remain relatively unaffected initially, and therefore circumferential strain and twist may remain normal or show exaggerated compensation for preserving LV systolic performance. Increase in cardiac muscle stiffness, however, may cause progressive delay in LV untwisting. Loss of early diastolic longitudinal relaxation and delayed untwisting attenuates LV diastolic performance, producing elevation in LV filling pressures and a phase of predominant diastolic dysfunction, although the LV ejection fraction may remain normal. On the other hand, an acute transmural insult or progression of disease results in concomitant midmyocardial and subepicardial dysfunction, leading to a reduction in LV circumferential and twist mechanics and a reduction in LV ejection fraction. Assessment of myocardial mechanics, therefore, can be tailored per the clinical goals. The detection of altered longitudinal mechanics alone may suffice if the overall goal of analysis is to detect the presence of early

Table 1 Classification of cardiac mechanics in heart failure

Functional impairment	Longitudinal mechanics	Circumferential mechanics	Radial mechanics	Torsional mechanics	Global EF	Diastolic filling pressures	Clinical syndrome
Predominant subendocardial dysfunction	Marked impairment	Preserved	Preserved/minimal impairment	Preserved	Preserved/minimal impairment	Elevated	Diastolic HF/HFNEF
Predominant subepicardial dysfunction	Preserved/minimal impairment	Marked impairment	Minimal impairment	Marked impairment	Preserved/minimal impairment	Elevated	Diastolic HF/HFNEF
Transmural dysfunction	Marked impairment	Marked impairment	Marked impairment	Marked impairment	Marked impairment	Elevated	Systolic HF

EF, Ejection fraction; *HF*, heart failure; *HFNEF*, heart failure and normal ejection fraction.

myocardial disease. Further characterization of radial strains, circumferential strains, and torsional mechanics provides assessment of the transmural disease burden and provides pathophysiologic insight into the mechanism of LV dysfunction. For example, pericardial diseases, such as constrictive pericarditis, cause subepicardial tethering and predominantly affect LV circumferential and torsional mechanics. The presence of attenuated longitudinal mechanics in constrictive pericarditis may signify the presence of transmural dysfunction. As another example, a pathophysiologic process such as radiation that affects both the pericardium and the subendocardial region may produce attenuation of both longitudinal and circumferential LV function.

The following sections comprehensively overview the application of STE in common cardiovascular diseases affecting LV function. For this, we performed a search of the Ovid Medline database and identified English-language articles relevant to strain imaging and cardiac function in human subjects (see the Appendix for details of the search strategy). The primary outcomes of each study for the following sections are reported in written and table format.

CORONARY ARTERY DISEASE

The subendocardium is the area of the left ventricle most vulnerable to the effects of hypoperfusion and ischemia.[35] LV longitudinal mechanics at rest may therefore be attenuated in patients with coronary artery disease (Table 2). For example, Liang et al[36] found that a peak longitudinal strain rate of $-0.83\ s^{-1}$ and an early diastolic strain rate of $0.96\ s^{-1}$ obtained from resting echocardiography could predict >70% coronary stenosis with sensitivity of 85% and specificity of 64%. Speckle tracking–derived longitudinal strain is also useful in predicting the extent of coronary artery disease. Choi et al[37] reported that a segmental mid and basal peak longitudinal strain cutoff value of −17.9% was capable of discriminating severe 3-vessel or left main coronary artery disease from disease with lesser severity with sensitivity of 78.9% and specificity of 79.3%.

MYOCARDIAL INFARCTION

Consistent with DTI, longitudinal strains are significantly reduced in patients with myocardial infarctions, proportionately within the area of infarction,[38-41] and correlate closely with peak infarct mass and ejection fraction[42-44] (Table 2). Patients with smaller infarcts and preserved global LV ejection fractions show reduced radial and longitudinal strain, although LV circumferential strains and twist mechanics remain relatively preserved.[45] In contrast, a larger transmural infarction is associated with additional reduction of circumferential strains[45] (Figure 2). In addition to normal strains, systolic twist and diastolic untwist are also reduced and correlate with the reduction in the LV ejection fraction.[45,46] Bertini et al[47] found that both the peak LV twist and untwisting rate are reduced in acute myocardial infarctions and correlate with the grade of diastolic and systolic LV dysfunction.

Speckle-tracking strains have increased sensitivity and specificity in comparison with tissue Doppler for determining the transmural extent of a myocardial infarction. Using a longitudinal strain cutoff value of −15%, Gjesdal et al[42] reported that infarcted segments could be detected with sensitivity of 76% and specificity of 95% at the segmental level and 83% and 93%, respectively, at the global level. Becker et al[48] compared radial and circumferential strains by speckle

Table 2 Studies assessing strain and twist in CAD

Study	Subjects (n)	Purpose	Principal observations
Resting echocardiography			
Choi et al (2009)[37]	CAD (66), controls (30)	Assessment of LS in CAD	LS correlated with the degree of coronary artery stenosis
Liang et al (2006)[36]	CAD (39), controls (15)	Assessment of LS in CAD	Decreased LS in ischemic segments
Stress echocardiography			
Bansal et al (2008)[52]	MI (44), no MI (41)	LV rotation with DSE	LV rotation reduced in infarcted segments but not in ischemic regions
Chan et al (2006)[43]	MI (80)	Transmurality of MI by DSE and CE-MRI	Transmural infarcts showed lower CS, but similar LS and RS as subendocardial infarcts
Hanekom et al (2007)[50]	CAD (150)	STE and DTI compared during DSE	Correlation better in anterior than posterior circulation
Ishii et al (2009)[51]	Stable angina (162)	Assessment of LS during stress test	LS detected CAD with 97% sensitivity and 93% specificity
MI/chronic CAD/ICM			
Becker et al (2006)[48]	MI (47)	Transmurality of MI, STE vs CE-MRI	RS had 70% sensitivity and 71% specificity in identifying non-transmural MI
Bertini et al (2009)[47]	MI (50), ICM (49), non-ICM (38), controls (28)	Evaluation of LV twist	Reduced twist in all patient populations correlated with LV systolic function
Chen et al (2007)[144]	MI (20), controls (15)	LV strain in MI	Reduced LS in comparison with controls
Gjesdal et al (2007)[42]	MI (38), controls (15)	Comparison with CE-MRI	LS had 83% sensitivity and 93% specificity in identifying MI
Delgado et al (2008)[44]	STEMI (99), ICM (123), controls (20)	LS compared with LV EF	LS correlated with LV EF
Jurcut et al (2008)[38]	MI (32), controls (20)	Comparison with CE-MRI	LS had 91% sensitivity and 90% specificity in identifying MI
Park et al (2008)[40]	No remodeling (28), remodeling (22)	Prediction of remodeling following revascularization	LS independently predicted LV remodeling
Roes et al (2009)[16]	CAD (90)	Comparison with CE-MRI	LS discriminated transmural from non-transmural scar
Takeuchi et al (2007)[45]	MI (30), controls (15)	LV twist in MI	CS and twisting velocity was reduced in patients with low EF
Revascularization/medical therapy			
Blondheim et al (2007)[55]	ICM (21)	Effects of medical therapy	Improvement in segmental LS
Becker et al (2008)[57]	MI (53)	Comparison with CE-MRI	RS predicted functional recovery (sensitivity, 70%; specificity, 85%)
Bertini et al (2009)[39]	MI (157)	Comparison with door-to-balloon times	Reduced LS correlated with cTnT and door-to-balloon times
Park et al (2008)[40]	No remodeling (28), remodeling (22)	LS in AMI following revascularization	LS independently predicted LV remodeling
Han et al (2008)[56]	MI (35), controls (32)	Twist in MI following revascularization	Improvement in twist following revascularization
Hoffmann et al (2009)[58]	MI (59)	Effect of revascularization, STE compared with CE-MRI	Peak systolic RS predicted functional recovery
Ishii et al (2009)[53]	CAD (30)	Effects of balloon occlusion	Reduction LS in affected and at-risk segments during occlusion
Winter et al (2007)[54]	CAD (8)	Effects of balloon occlusion	Decreased RS and CS

AMI, Acute myocardial infarction; *CAD*, coronary artery disease; *CE-MRI*, cardiac MRI; *CS*, circumferential strain; *cTnT*, cardiac troponin T; *DSE*, dobutamine stress echocardiography; *EF*, ejection fraction; *ICM*, ischemic cardiomyopathy; *LS*, longitudinal strain; *MI*, myocardial infarction; *RS*, radial strain; STEMI, ST-elevation myocardial infarction.

tracking with the extent of infarction as delineated by contrast-enhanced MRI (Table 2). Using a segmental radial strain cutoff value of 16.5%, nontransmural infarcts could be distinguished from transmural infarcts with sensitivity of 70.0% and specificity of 71.2%. On the other hand, a circumferential strain value $< -11.10\%$ distinguished nontransmural infarction from transmural infarction with sensitivity of 70.4% and specificity of 71.2%.[48] Roes et al[16] identified that a regional longitudinal strain cutoff value of -4.5% could distinguish a nontransmural infarct from a transmural infarct with sensitivity of 81.2% and specificity of 81.6% (Table 2).

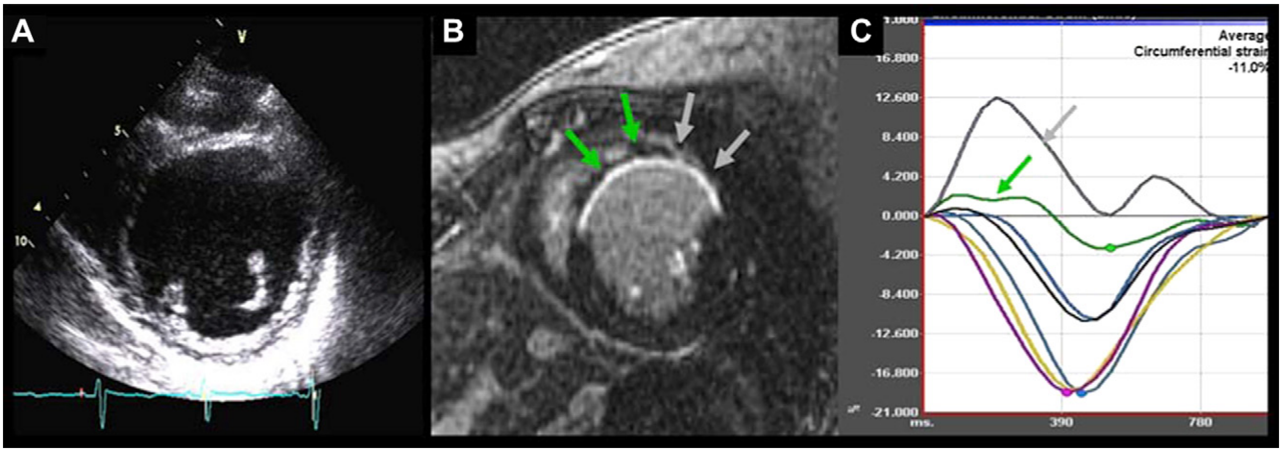

Figure 2 Circumferential strains in a 37-year-old female patient with transmural anteroseptal myocardial infarction. Panels **A** and **B** show the cross-sectional view of the left ventricle obtained on 2D echocardiography and MRI, respectively. Note the transmural enhancement seen on delayed enhancement MRI *(gray and green arrows)*. Panel **C** shows the circumferential strain (2D Cardiac Performance Analysis; TomTec, Munich, Germany) obtained from 6 LV segments. Dyskinetic circumferential strain is recorded from anterior and anteroseptal segments *(grey and green arrows)*, where there is evidence of transmural scarring.

STRESS ECHOCARDIOGRAPHY

Tissue Doppler technology has shown that patients with newly developed myocardial ischemia have reduced peak longitudinal, circumferential, and radial systolic strains during dobutamine infusion, with the greatest deterioration of myocardial shortening occurring in the circumferential direction.[49] In comparison with tissue velocity–derived strains, speckle tracking longitudinal strains during dobutamine stress echocardiography have similar accuracies for detecting ischemia in the left anterior descending coronary artery territory but reduced accuracy for the left circumflex and right coronary artery territories[50] (Table 2). This may be due to the dependency of 2D strain on grayscale image quality.

The crossover sequence from systole to diastole is the most energy demanding phase of the cardiac cycle. In the ischemic cascade, diastolic dysfunction therefore develops earlier than the appearance of regional systolic wall motion abnormalities. Speckle tracking–derived strain values measured in diastole may have superior sensitivity for identifying ischemic regions.[51] For example, Ishii et al[51] measured regional LV radial strain obtained from apical long-axis views (also referred to as transverse strains) during the first third of diastole (strain imaging diastolic index) and at baseline and 5 and 10 minutes after exercise. A strain imaging diastolic index ratio of 0.74 detected significant coronary artery disease (>50% stenosis of $\geq$1 large coronary vessel) with sensitivity of 97% and specificity of 93%.[51] More investigations are required to further clarify the diagnostic utility of measuring diastolic strain indices in patients with coronary artery disease.

Speckle-tracking strains have also been used in conjunction with low-dose dobutamine for detecting viability and myocardial contractile reserve. Myocardial segments with transmural scars show reduced contractile reserve with dobutamine infusion.[43] Circumferential strains are particularly useful in differentiating transmural from nontransmural infarctions.[43] Torsion is reduced in infarcted segments but not within ischemic regions.[52]

REVASCULARIZATION

The effects of balloon occlusion and time to reperfusion on regional myocardial function have been evaluated using STE. Balloon occlusion during catheterization of the coronary arteries results in a transient reduction in systolic and diastolic strain at the proximal and distal at-risk segments, which return to normal following reperfusion.[53] Shorter symptom-to-balloon times in patients with acute coronary syndromes typically result in lower impairment of systolic longitudinal strain, which relates closely to peak levels of cardiac troponin T.[39,54] Speckle-tracking strains are useful in predicting myocardial segments with resting dysfunction following revascularization that will likely improve on follow-up[55,56] (Table 2). Park et al[40] reported that longitudinal strain $< -10.2\%$ following reperfusion therapy in patients with acute myocardial infarction predicted nonviable myocardium in a remodeled left ventricle with sensitivity of 90.9% and specificity of 85.7%. In addition, longitudinal strain $< -6.4\%$ predicted the development of heart failure or death with sensitivity of 81.8% and specificity of 84.6%.[40] STE-derived peak radial strain correlates with the extent of hyperenhancement on delayed contrast-enhanced MRI. Becker et al[57] found that by using a cutoff of 17.2% for peak systolic radial strain, one could predict functional recovery with sensitivity of 70.2% and specificity of 85.1%, similar to results using contrast-enhanced MRI (sensitivity, 71.6%; specificity, 92.1%). Another study combined delayed hyperenhancement seen on contrast-enhanced MRI incrementally with radial deformation patterns observed on STE and showed sensitivity of 82.2% and specificity of 78.3% for predicting segmental functional recovery.[58]

VALVULAR DISEASE

Because of adaptive remodeling of the left ventricle, patients can remain asymptomatic or minimally symptomatic for prolonged periods, even in the presence of severe valvular disease. STE improves the yield of routine 2D echocardiography in valvular heart diseases by providing insights into the pattern of adaptive remodeling and detecting the presence of subclinical cardiac dysfunction.

Aortic Stenosis

Aortic stenosis results in progressive LV hypertrophy due to increased afterload. The LV ejection fraction, however, remains preserved. Previous studies with DTI established that LV systolic longitudinal

Table 3 Studies evaluating myocardial strain in valvular disease

Study	Subjects (n)	Purpose	Strain/twist
AS			
Becker et al (2007)[63]	AS (22)	RS and CS in AVR	Improved RS and CS after AVR
Tzemos et al (2008)[64]	Pregnancy with AS (10); pregnancy, no AS (10); controls (10)	RS in AS with pregnancy	No change in RS prepartum or postpartum; higher twist in pregnancy with AS
Lafitte et al (2009)[62]	AS (65), controls (60)	Exercise stress test in severe AS	Reduced LS with stress testing with preserved CS and RS
AI			
Becker et al (2007)[63]	AI (18)	Strain before and after AVR	Reduction in CS and RS after AVR
Gabriel et al (2008)[65]	AI (39), controls (10)	GLS in AI with stress echocardiography and BNP	No association between GLS and plasma BNP levels
Stefani et al (2009)[67]	AI (20), no AI (40)	Strain in athletes with AI	Reduced LS in basal regions with basal-to-apical gradient
MR			
Borg et al (2008)[71]	Patients (38), controls (30)	LV torsion in MR	Delayed and reduced rate of LV untwisting
Kim et al (2009)[70]	Preserved contractility (30), reduced contractility (29), controls (34)	Strain in MR and contractility	Reduced LS, RS, and CS in reduced contractile function
Lancellotti et al (2008)[69]	Patients (71), controls (23)	Strain at rest and after exercise stress echocardiography	Reduced LS in patients with blunted response to exercise

AI, Aortic insufficiency; *AS*, aortic stenosis; *AVR*, aortic valve replacement; *BNP*, brain natriuretic peptide; *CS*, circumferential strain; *GLS*, global longitudinal strain; *LS*, longitudinal strain; *LV*, left ventricle; *MR*, mitral regurgitation; *RS*, radial strain.

strain and strain rate are significantly attenuated in patients with aortic stenosis and improve immediately following aortic valve replacement.[59,60] Similarly, speckle tracking–derived longitudinal strains have also been shown to be reduced in severe aortic stenosis.[61] However, radial and circumferential strains and LV twist mechanics remain relatively preserved[62] (Table 3, Figure 3). In addition, LV deformation shows improvement in all the 3 normal directions following aortic valve replacement.[62,63] Tzemos et al[64] reported an increase in LV twist in pregnant patients with aortic stenosis.

Aortic Insufficiency

Aortic regurgitation is characterized by a significant increase in LV end-diastolic volume and preload. Compensation through remodeling and ventricular dilatation masks the onset of clinical LV dysfunction.[65] DTI-derived longitudinal and radial peak systolic strain rates have been previously reported to be decreased in patients with severe aortic regurgitation and correlated significantly with LV end-systolic and end-diastolic volume.[66] Similarly, global longitudinal strain derived by STE is reduced in aortic insufficiency in patients with bicuspid aortic valves.[67] Also, speckle tracking–derived circumferential and radial strains are reduced immediately following aortic valve replacement because of immediate changes in LV loading parameters, and a modest improvement is seen after 6 months[63] (Table 3).

Mitral Regurgitation

Previous studies using DTI-derived strains reported that both longitudinal and radial strain are reduced in severe mitral regurgitation and are directly related to the LV stroke volume, diameter, and contractility.[68] Similarly, STE-derived longitudinal strain rates have been reported to be attenuated in severe mitral regurgitation earlier than circumferential and radial strain rates[69,70] (Table 3). The appearance of contractile dysfunction also results in attenuation of the circumferential and radial strain rates.[70] In contrast, LV twist mechanics may remain preserved in patients with mitral regurgitation, including peak systolic twist, systolic twist velocity, and untwisting velocity.[71]

LEFT VENTRICULAR HYPERTROPHY

STE has been used in detecting subclinical myocardial changes in LV hypertrophy, as well as in distinguishing the different causes of LV hypertrophy.

Physiologic Hypertrophy

Several speckle-tracking echocardiographic studies have attempted to decipher the complex adaptive changes in LV mechanics seen with exercise. Most studies identified a significant increase in strains[72] and the development of a higher regional function reserve during high-intensity training.[73,74] Endurance training, however, results in reductions in peak longitudinal, circumferential, and radial strains.[75] Nottin et al[76] reported reduced peak radial strain at the LV apical level in cyclists in comparison with controls, despite normal peak circumferential shortening (Table 4). Endurance training in rowers has been reported to result in increase radial strain equally in all segments, decrease in longitudinal strain increases from the base toward the apex, and an increase in circumferential strain in the LV free wall with reductions in the septum due to changes in RV structure.[72,77] LV twist may be reduced with endurance training. For example, Zocalo et al[78] reported reductions in LV twist in soccer players that occurred conjunctly with the development of higher ejection fractions. Similarly, cyclists have been reported to experience reductions in LV twist.[76] Surprisingly, reduced twist has not been identified by all authors. Neilan et al[79] found increased twist following exercise in athletes. In addition, exercise may result in a delay in age-related reduction in LV longitudinal function. For example, elderly marathon runners showed no evidence of LV systolic dysfunction following a marathon with preserved longitudinal strain and fractional shortening.[80] The underlying physiologic mechanisms for explaining the variability of these data remain yet to be established.

Hypertensive Heart Disease

Hypertensive heart disease is characterized by cardiac hypertrophy in response to increased cardiac afterload, followed by progressive

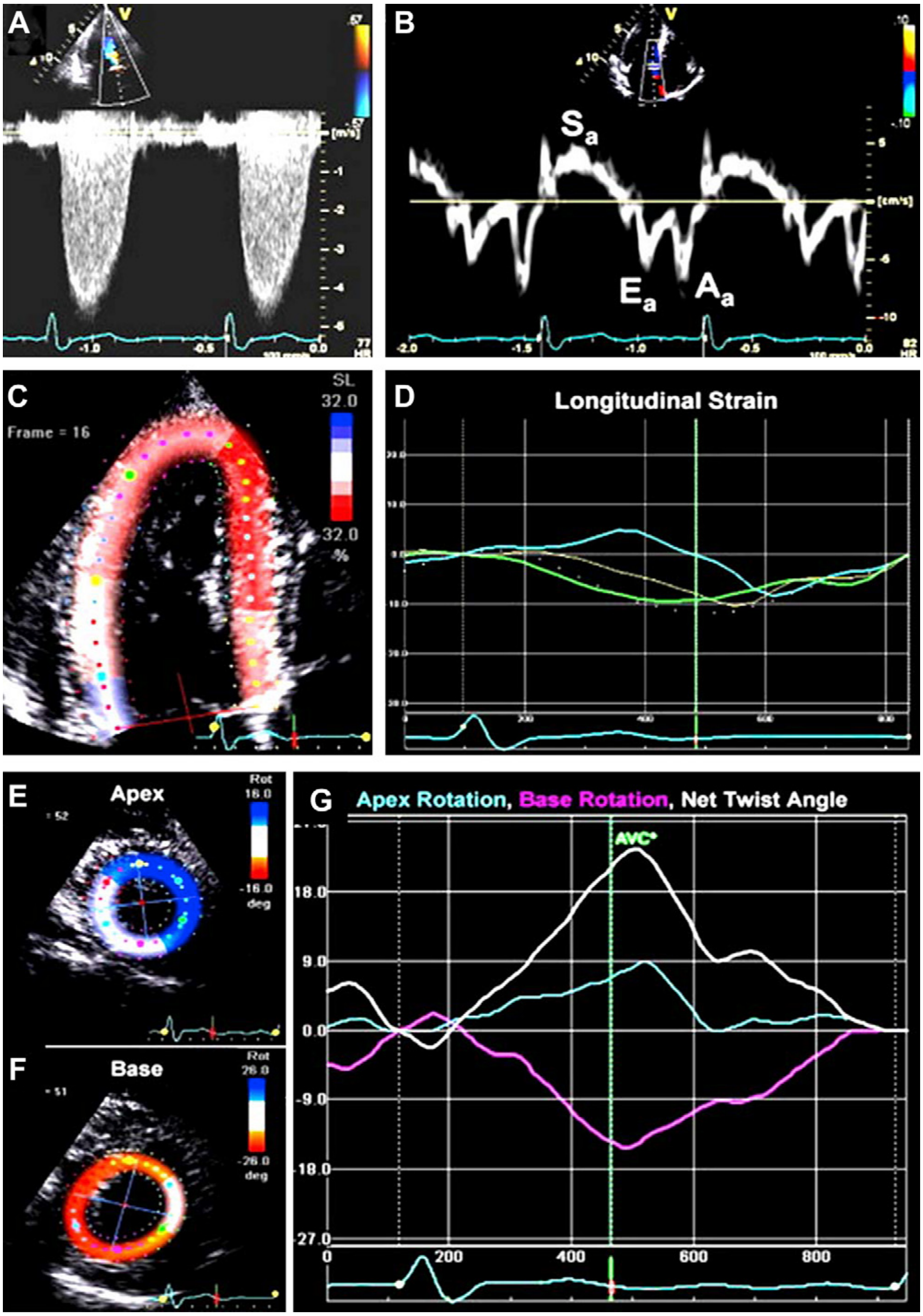

Figure 3 LV mechanics in aortic stenosis. Continuous-wave Doppler signal across the stenotic aortic valve in panel **A** shows peak and mean gradients of 80 and 44 mm Hg, respectively. Pulsed-wave tissue Doppler from the septal corner of the mitral valve annulus in panel **B** shows a reduced peak early diastolic longitudinal relaxation velocity (5 cm/s). Longitudinal strain obtained by speckle tracking (2D strain; GE Healthcare, Milwaukee, WI) shows attenuated peak longitudinal strain in panels **C** and **D** from apical *(green curve)*, mid *(yellow curve)*, and basal *(blue curve)* of the lateral wall of the left ventricle (peak strain values < 10%). The *dotted white line* in panel **D** also shows a reduced global longitudinal strain averaged from the septum and lateral wall of the left ventricle (global strain = 12%). Peak counterclockwise rotation from the apex **(E)** and clockwise rotation from the base **(F)** are obtained by speckle-tracking imaging. The difference of the two rotational values provides the peak net twist angle. This example illustrates the presence of exaggerated LV rotation, particularly near the LV base with a relatively high net LV twist angle value. A_a, peak late diastolic annular velocity; *AVC*, aortic valve closure; E_a, peak early diastolic annular velocity; S_a, peak systolic velocity during ejection. Reproduced with permission from *J Am Coll Cardiol*.[61]

Table 4 STE in physiologic hypertrophy

Study	Subjects (n)	Purpose	Strain/twist
Baggish et al (2008)[72]	Athletes (20)	Strain in athletes following exercise	Increased LS with a basal-to-apical gradient, increased CS in LV free wall, reduced adjacent to RV, increased RS during exercise.
George et al (2009)[75]	Athletes (19)	Strain in athletes during exercise	Reduced LS, RS, and CS following exercise
Knebel et al (2009)[80]	Athletes (28), control (50)	Evaluated strain and BNP with age following exercise	Reduced LS in right ventricular free wall with no correlation to BNP
Neilan et al (2006)[79]	Athletes (17)	Torsion in athletes after exercise	Increased torsion after exercise
Nottin et al (2008)[76]	Patients (16), controls (23)	Strain and twist in athletes at rest	Reduced RS at apex along with reduced twist
Richand et al (2007)[77]	Athletes (29), HCM (26), controls (17)	Strain in physiologic hypertrophy and HCM	LS, CS, and RS lower in HCM then physiologic hypertrophy
Stefani et al (2008)[73]	Athletes (25), controls (25)	Strain during handgrip test	Increased regional functional reserve of LS in medium-apical segments
Stefani et al (2009)[74]	Athletes (20), controls (18)	Strain during handgrip test	Greater LS in RV than LV in patients and controls
Zocalo et al (2007)[78]	Patients (16), controls (6)	LV torsion in athletes at rest	Reduced twist and basal and apical RS in athletes

BNP, Brain natriuretic peptide; *CS*, circumferential strain; *HCM*, hypertrophic cardiomyopathy; *LS*, longitudinal strain; *LV*, left ventricle; *RS*, radial strain; *RV*, right ventricle.

Table 5 Studies evaluating myocardial strain in hypertensive heart disease

Study	Subjects (n)	Purpose	Strain/twist
Kang et al (2008)[81]	HTN (56), control (20)	Strain and collagen turnover in HTN	Increased twist, preserved RS and CS, and reduced LS which correlated with procollagen peptide levels
Takeuchi et al (2007)[83]	Patients (49)	Torsion in LVH	Reduced twist which correlated with degree of hypertrophy
Palmieri et al (2009)[84]	HTN (26)	LV mechanics before and after β_1 blockade in HTN	Decreased LS and CS following β_1 blockade
Han et al (2008)[82]	Patients (50), controls (45)	LV twist in HTN	Higher peak systolic twist ($P < .001$) and reduced untwisting rates
Chen et al (2007)[46]	Patients (20), controls (20)	Strain in HTN with LVH	Reduced LS rates with preserved CS rates
Chirinos et al (2009)[145]	Untreated HTN (42), treated HTN (42), controls (42)	Evaluated stress-strain relationship in HTN	Midsystolic shift in stress-strain relationship

CS, Circumferential strain; *HTN*, hypertension; *LS*, longitudinal strain; *LV*, left ventricle; *LVH*, LV hypertrophy; *RS*, radial strain.

myocardial fibrosis. Speckle tracking–derived longitudinal strains are reduced in hypertension, while LV radial and circumferential strains remain well preserved[46,81] (Table 5). Torsional mechanics are also preserved. However, the untwisting may be abnormal and delayed. For example, Han et al[82] reported that peak LV twist is increased in systemic hypertension, while untwisting velocity is reduced. Although others have reported that peak systolic twist remains normal, early diastolic LV untwisting velocity during the isovolumic relaxation period is reduced and delayed and correlates with the degree of LV hypertrophy.[82,83] Beta-blocker therapy leads to adaptation of LV systolic mechanics such that a reduction in longitudinal contractility is associated with improvements in circumferential strain and stroke volume[84] (Table 5).

Hypertrophic Cardiomyopathy

Hypertrophic cardiomyopathy (HCM) is characterized by myocardial fiber disarray, which results in LV systolic and diastolic dysfunction. Investigations with tissue Doppler–derived strains previously reported marked abnormalities in LV longitudinal mechanics ranging from reduced or delayed shortening to paradoxical systolic lengthening,[85] which helps distinguish HCM from other causes of LV hypertrophy.[86] Similarly, STE has revealed that longitudinal strain in patients with HCM is reduced in proportion to patient symptoms.[87] The amount and location of LV fibrosis (Figure 4) and end-diastolic wall thickness are independent predictors of end-systolic longitudinal strain[88] (Table 6). Depending on the extent of myopathy, the extent of compensation offered by circumferential strain in relation to the reduction in longitudinal strain in HCM may vary.[87,89] Left atrial longitudinal strain has also been evaluated as a surrogate marker of LV pressure. Paraskevaidis et al[90] determined that HCM could be distinguished from non-HCM LV hypertrophy by using an atrial longitudinal strain cutoff value of −10.82% with sensitivity of 82% and specificity of 81%. Reddy et al[91] evaluated strain patterns in apical variant HCM and found a progressive increase in longitudinal strain from base to apex with paradoxical longitudinal systolic lengthening in apical segments.

Marked variability in LV systolic twist patterns may be seen in HCM depending on the pattern and the extent of hypertrophy[92] (Table 5). LV twist may also be apically displaced, resulting in the

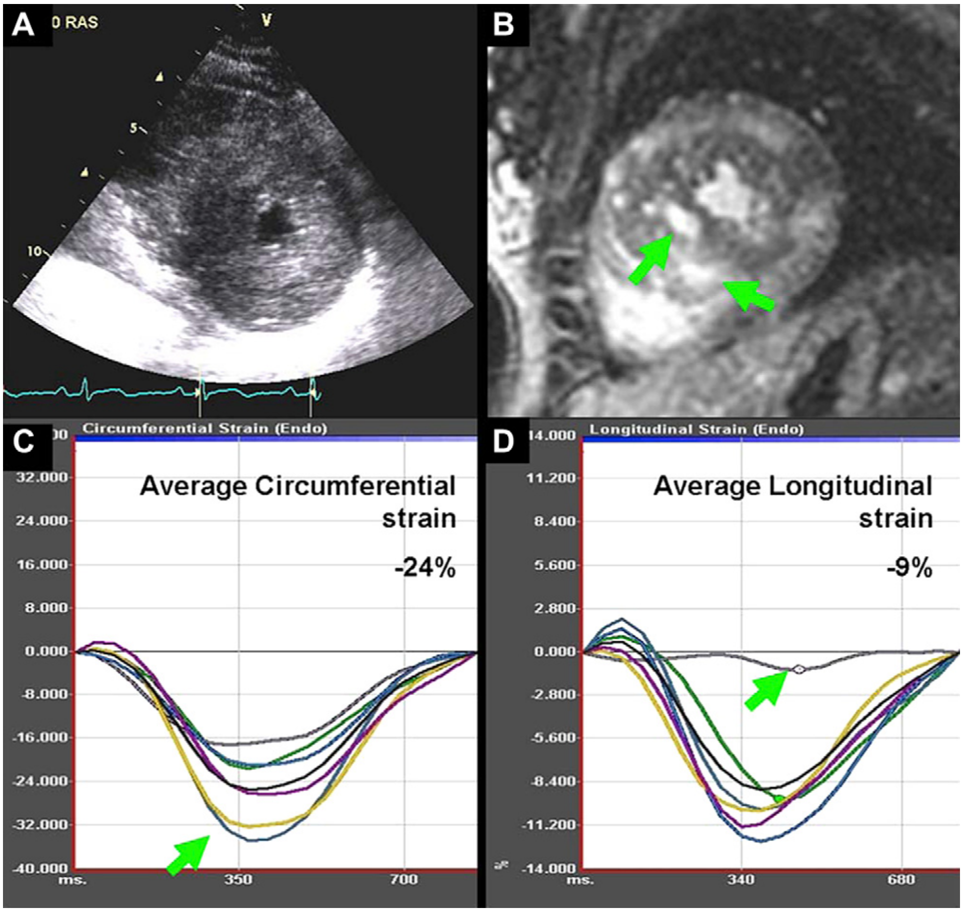

Figure 4 Myocardial mechanics in a 21-year-old female patient with hypertrophic cardiomyopathy. Panels **A** and **B** show the cross-sectional view of the left ventricle obtained from 2D echocardiography and MRI, respectively. Note the localized and spotty enhancement seen on delayed enhanced MRI *(green arrows)*. Panels **C** and **D** show the disparate patterns of shortening mechanics (2D Cardiac Performance Analysis; TomTec, Munich, Germany). Midinferior segments **(C)** *(green arrow)* show preserved circumferential strains, whereas the same segment shows marked attenuation of longitudinal strain **(D)** *(green arrow)*.

appearance of clockwise rotation in the mid LV region.[87,93] Untwisting is significantly impaired and correlates with LV end-diastolic pressure, volume and VO_2max[94] (Table 6). Following septal ablation, substantial changes may occur in LV strains and twist mechanics. Longitudinal strains are reduced at the infarct site and improved in distant segments, while LV twist may exceed baseline values one week after ablation[93] (Table 5).

DILATED CARDIOMYOPATHY

Dilated cardiomyopathy is associated with reduction of strains in all 3 directions[95-97] (Table 6). LV rotation is reduced at the base and the apex, leading to attenuation of LV twist[95-97] and untwisting velocity.[98] Patients with fewer symptoms usually exhibit higher longitudinal strain and strain rate.[99] Paradoxical reversal of direction of LV rotation may be seen, with the LV base showing counterclockwise rotation and the apex showing clockwise end-systolic rotation.[95,98]

STRESS CARDIOMYOPATHY

Stress cardiomyopathy (also termed "takotsubo cardiomyopathy") is a more recently described form of reversible LV systolic dysfunction. The most common form of stress cardiomyopathy is transient apical ballooning syndrome. STE has provided unique insights into the pattern of dysfunction characterized by systolic dysfunction and reduction of LV strains in a segmental territory that extends beyond any single vascular distribution pattern.[100] A variety of abnormal strain patterns have been reported. Mansencal et al[100] identified that peak systolic strain and strain rate are reduced in both the basal and apical regions in takotsubo patients during the active phase; these abnormalities improve during recovery.[101] Others have shown the presence of hyperkinesis within the basal regions,[102] attenuation of the longitudinal strain in the midmyocardial segments,[103] or dyskinesis at the LV apex[91,102] (Table 6). LV strains normalize at 1-month follow-up.[100,101,103] In general, strain abnormalities in takotsubo cardiomyopathy show a distribution that does not follow a specific coronary artery territory; a feature that is useful in distinguishing this condition from acute coronary syndromes.

PERICARDIAL DISEASES AND RESTRICTIVE CARDIOMYOPATHY

The pericardium has been suggested to have permissive action for facilitating LV twist deformation. Loss of normal compliance of pericardial tissue therefore alters the pattern of LV torsional recoil. For example, in congenital absence of the pericardium, LV torsion is significantly reduced, despite preservation of the longitudinal, radial, and

Table 6 Studies evaluating cardiac strain in cardiomyopathies

Study	Subjects (n)	Purpose	Strain/twist
HCM			
Carasso et al (2008)[87]	HCM (72), controls (32)	Strain in HCM	Reduced LS and increased CS with paradoxical rotation pattern
Carasso et al (2008)[93]	HCM (21), controls (24)	Strain during septal ethanol ablation in HCM	Reduced LS and increased CS normalized postprocedurally
Paraskevaidis et al (2009)[90]	HCM (43), LVH (21), controls (27)	Left atrial longitudinal function in HCM and LVH	Reduced left atrial strain in HCM
Popovic et al (2008)[88]	HCM without fibrosis (16), HCM with fibrosis (23), controls (23)	Fibrosis in HCM with STE and CE-MRI	Reduced CS and RS in HCM with and without fibrosis; reduced LS in HCM with fibrosis
Reddy et al (2008)[91]	Apical variant HCM (2)	Strain in apical variant HCM	Reduced CS in mid-myocardium with paradoxically increased apical strain
Serri et al (2006)[89]	HCM (26), controls (45)	Strain in HCM	Reduced LS, CS, and RS
Sun et al (2009)[92]	HCM (20), secondary LVH (24), amyloid (12), controls (22)	Strain in HCM, secondary LVH, and amyloid	RS and LS decreased in HCM, but higher than amyloidosis; reduced twist in comparison with amyloidosis and controls
Wang et al (2009)[94]	HOCM (25), HCM (20), controls (20)	Strain and V_{O_2}max in HCM and HOCM during exercise testing	Reduced LS, CS, and RS in HOCM and HCM with delayed untwisting that correlated with V_{O_2}max
IDC			
Friedberg et al (2008)[96]	Patients (24), controls (16)	LV radial function in children with IDC	Reduced RS
Jasaityte et al (2009)[99]	Stable IDC (18), unstable IDC (20)	Strain in end-stage IDC in stable and unstable patients	Reduced LS in unstable IDC, with preserved RS and CS compared with stable IDC
Meluzin et al (2009)[95]	IDC (37), controls (14)	Strain in IDC	Reduced LS, CS, and RS and rotational amplitude
Saito et al (2009)[98]	IDC (101), controls (50)	Twist in IDC	Reduced peak twist with greater radial dyssynchrony
Zeng et al (2009)[97]	Patients (30), controls (30)	Radial strain in IDC	Reduced RS
TC			
Baccouche et al (2009)[102]	TC (1)	3D STE in TC	Increased RS with basal hypercontractility and apical dyskinesia
Burri et al (2008)[101]	TC (5)	Strain in TC during and after disease	Reduced LS with improvement after disease
Heggemann et al (2009)[103]	TC (12)	Strain in TC during and after disease	Reduced LS and RS with improvement after disease
Mansencal et al (2009)[100]	TC (14), ICM (14), controls (14)	Strain in TC and ICM	Circular systolic dysfunction in acute TC that normalized to mimic ICM pattern

CE-MRI, Cardiac MRI; *CS*, circumferential strain; *HCM*, hypertrophic cardiomyopathy; *HOCM*, hypertrophic obstructive cardiomyopathy; *ICM*, ischemic cardiomyopathy; *IDC*, idiopathic dilated cardiomyopathy; *LS*, longitudinal strain; *LV*, left ventricle; *LVH*, LV hypertrophy; *RS*, radial strain; *STE*, speckle-tracking echocardiography; *TC*, takotsubo cardiomyopathy.

circumferential systolic strains.[104] Similarly, constrictive pericarditis is characterized by significantly reduced circumferential strain and twist, while longitudinal strain is relatively preserved.[105] On the other hand, patients with restrictive cardiomyopathies, such as cardiac amyloidosis, have significant impairment of longitudinal strain. Circumferential strain and LV torsion may remain relatively preserved and maintain the LV ejection fraction.[105] However, progression of the disease finally leads to further impairment of LV circumferential strain (Figure 6).

EMERGING INSIGHTS IN CHARACTERIZING HEART FAILURE SYNDROMES

Traditional concepts of heart failure have largely focused on the hemodynamic consequences of LV systolic dysfunction. Using a time-dependent model of heart failure, it has been proposed that diastolic and systolic heart failure are phenotypic expressions of the same disease process that evolves gradually as a continuum of clinical events.[106] Assessment of cardiac mechanics by STE has helped uncover this continuum of heart failure syndromes. Patients with diastolic heart failure have attenuated global longitudinal strain which correlates with increased risk for cardiovascular events in ischemic heart failure.[107] However, circumferential and radial strain patterns in diastolic heart failure may vary, underscoring the continuum of the disease process.[108,109] In addition, LV torsion and peak untwisting rate are preserved in diastolic heart failure and have similar values to age-matched controls.[109,110] However, progression from diastolic to systolic heart failure may be characterized by a reduction in both peak LV twist and untwisting rate, which correlate with the grade of diastolic and systolic dysfunction.[47,110-112]

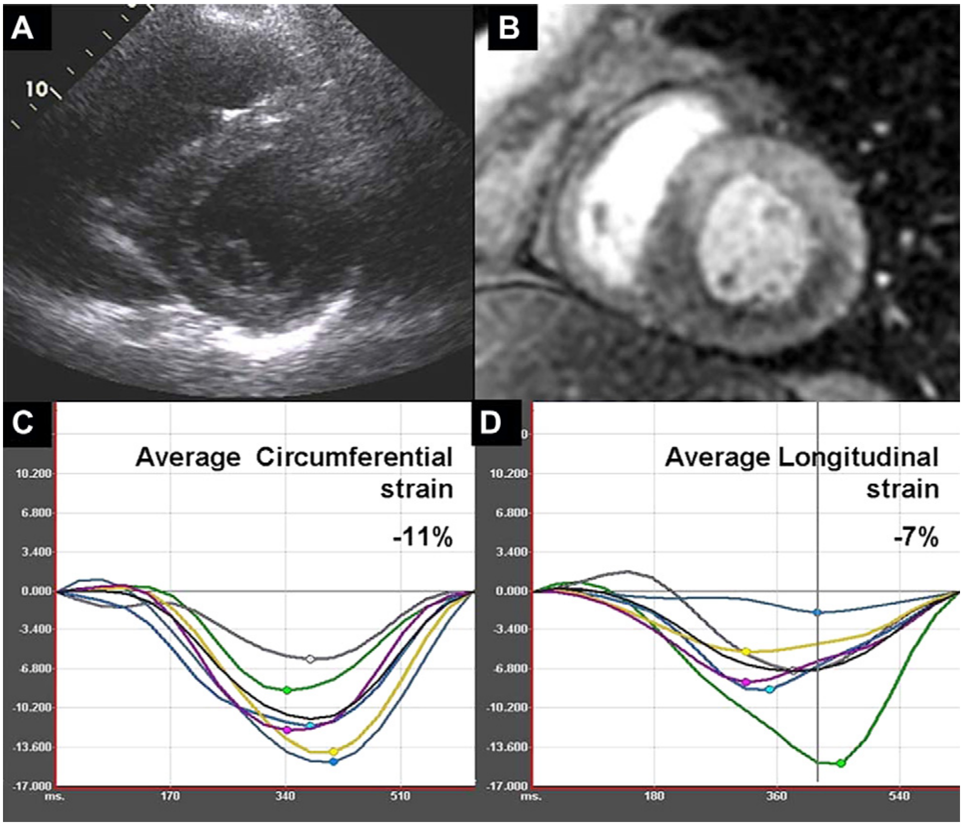

Figure 5 Myocardial mechanics in a 62-year-old female patient with amyloidosis. Panels **A** and **B** show the cross-sectional view of the left ventricle obtained with 2D echocardiography and MRI, respectively. Note the diffuse, transmural enhancement seen on delayed enhancement MRI. Both panels **C** and **D** show the reduced circumferential and longitudinal strain (2D Cardiac Performance Analysis; TomTec, Munich, Germany).

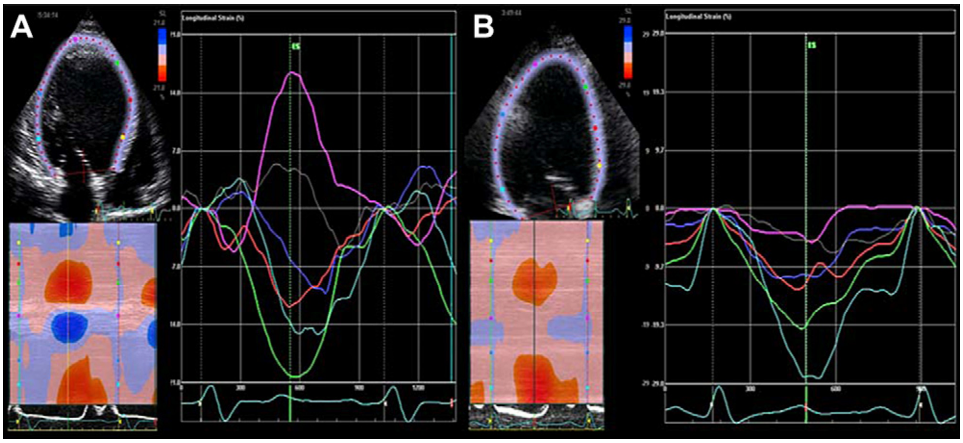

Figure 6 Dyssynchronous LV shortening in myocarditis. Panel **A** shows marked dyssynchrony of segmental longitudinal shortening strains obtained in a patient with myocarditis (2D strain; GE Healthcare, Milwaukee, WI). Panel **B** shows the improved synchrony of segmental shortening following therapy, which was accompanied with improved global systolic function.

Clinical acceptance of newer therapeutic techniques, such as cardiac resynchronization therapy (CRT), has fueled interest in using STE for assessing LV mechanical function. This remains an area of intense investigation and has been reviewed in depth recently by several investigators.[113,114] To summarize briefly, STE has allowed assessment of radial and circumferential components of myocardial motion for dyssynchrony analysis in determining the response to CRT, including the extent of LV dyssynchrony and the presence of

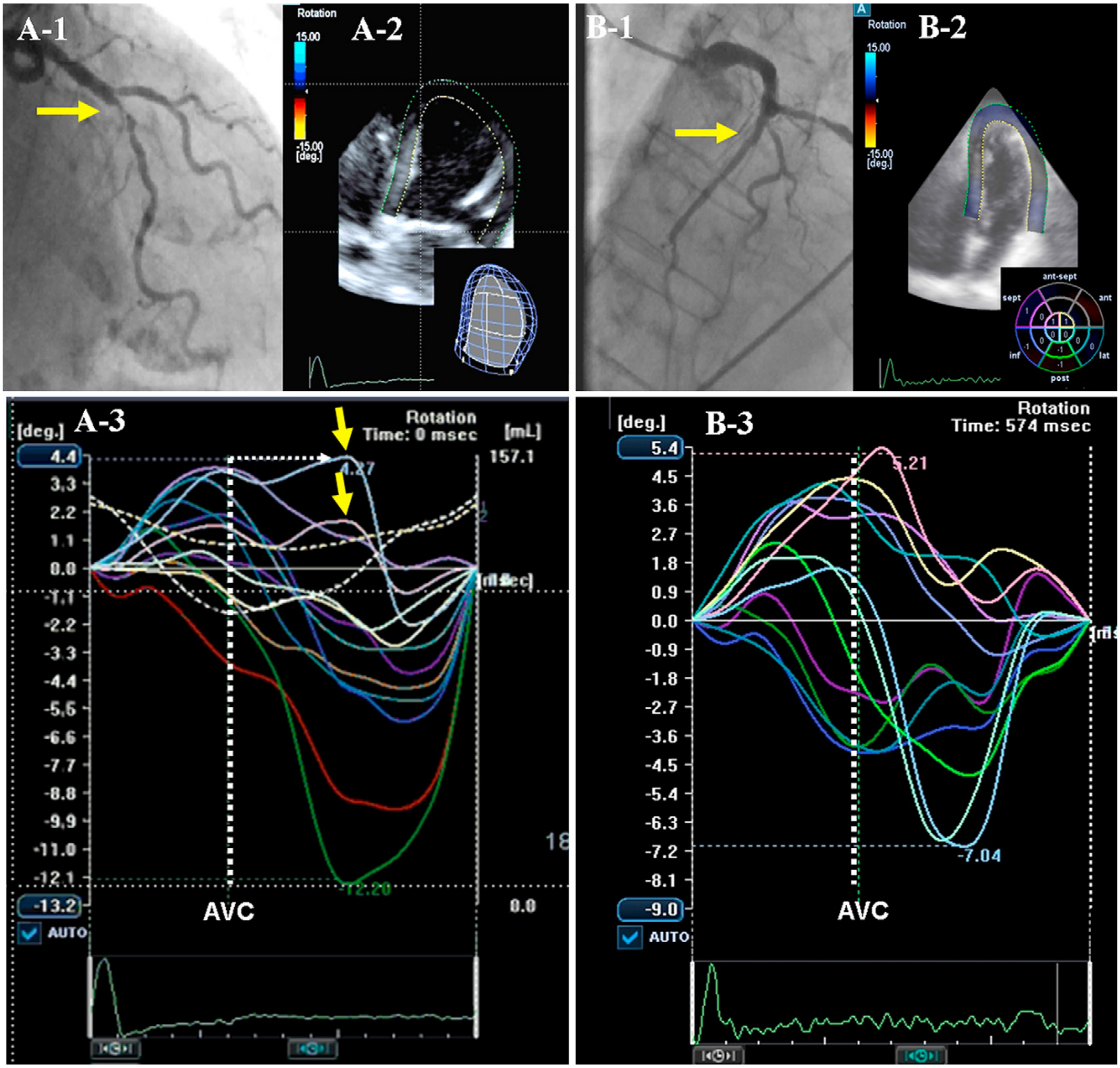

Figure 7 LV rotational mechanics using 3D STE. LV dysfunction **(A1-A3)** prior to revascularization of a lesion in left anterior descending coronary artery **(A1)** *(arrow)* with a reduced ejection fraction (28%), which was calculated using automated 3D speckle tracking. LV rotation in apical segments is attenuated **(A3)** *(arrows)* with delayed onset of untwisting in comparison with the timing of aortic valve closure (AVC). Following revascularization **(B1)** *(arrow)*, LV segmental rotation has marginally increased with marked improvement in the timing of untwisting **(B3)**.

contractile reserve.[115-118] Several novel indices have been explored using the timing of longitudinal strain[119] and radial strain[120,121] for predicting response to CRT in both ischemic and nonischemic patients. In general, responders experience a significant improvement in multidirectional strain along with reversal of LV remodeling and improvement in ejection fraction after CRT.[122] Similarly, an improvement in exercise-related longitudinal strain has been suggested to indicate the presence of contractile reserve and predict reversal of remodeling following CRT.[115,116] Speckle tracking has also allowed for explorations in LV twist mechanics for understanding LV dyssynchrony and its role in identifying responders to CRT.[111,123] Twist and LV ejection fraction significantly improve following CRT, primarily with apical and midventricular lead position placement.[111] Despite these extensive explorations, there is currently a lack of consensus on how LV mechanical indices should be assessed in patients undergoing CRT. Speckle tracking–derived strain estimates appear to be more reliable than DTI strain estimates. However, there is a need for large-scale multicenter trials before STE strain analysis techniques can be widely adopted. Intriguingly, improvement in mechanical dyssynchrony may be seen with medical therapy alone, such as in acute myocarditis, in which dramatic improvement may occur following resolution of the disease process.[124] Similarly, improvement in LV dyssynchrony has been reported in heart failure patients with novel therapies such as bone marrow–derived cell injection.[125] LV mechanical coordination may thus involve other variables that are beyond the electrical and mechanical domains and require further explorations in future investigations.

CONGENITAL HEART DISEASES

Because echocardiography represents the noninvasive tool most commonly used in pediatric cardiology, application of STE for bedside assessment of LV strain and twist deformation may provide important insights into mechanical adaptive responses of the right ventricle and left ventricle in congenital heart diseases. For example, in the normal heart, both the right and left ventricles are coupled for twisting in the same direction.[126] However, in patients with transposition of the great arteries, the morphologic right ventricle supports the systemic circulation. It has been shown recently that the systemic right ventricular (RV) contraction in these patients resembles that of the normal left ventricle, but without the ventricular twist.[127] The global performance of the systemic ventricle is dependent more upon the circumferential than the longitudinal free wall contraction and may represent an adaptive response to the systemic load.[22] As twist contributes to energy-efficient ejection, reduced twist might represent a potential for myocardial dysfunction.[127] However, this hypothesis requires further prospective evaluation.

There have been limited applications with STE in other congenital heart diseases. Patients with tetralogy of Fallot and right bundle branch block have been reported to have reduced strain in the lateral and septal LV walls.[128] Patients with atrial septal defects show evidence of reduced LV systolic twist.[129] However, there are significant improvements in basal rotation and peak clockwise rotation following atrial septal device closure, along with reductions in RV global longitudinal strain.[130,131] These changes likely reflect the reversal of cardiac remodeling as the heart undergoes reductions in end-diastolic RV diameter and pressure, with improved LV filling postprocedurally.

SUBCLINICAL CARDIAC INVOLVEMENT IN SYSTEMIC DISEASES

STE is useful in preclinical detection of cardiac involvement in systemic diseases. For example, recent studies in type 1 diabetes mellitus have identified increased torsion, suggesting the presence of subclinical microvascular disease.[132] This increase in LV torsional deformation seen in diabetes helps in compensating for reduction in the global longitudinal strain.[133-136] Circumferential and radial function may vary, depending on the severity of cardiac muscle involvement.[134,136] Impaired LV longitudinal and circumferential shortening may occur in other endocrine abnormalities, such as Cushing's disease, and normalize upon correction of the corticosteroid excess.[137]

STE may also be useful for monitoring effects of novel therapies and for detecting cardiotoxicity. For example, improved endothelial function following use of anakinra, an interleukin-1 receptor antagonist, in rheumatoid arthritis was associated with increased longitudinal and circumferential strain and strain rates.[138] Cardiotoxic chemotherapeutic agents, including trastuzumab and anthracyclines, have been successfully characterized by DTI.[139,140] Similarly, a recent study using STE evaluated trastuzumab therapy in breast cancer patients and revealed subclinical cardiotoxicity with significant reductions in radial strain rate, despite no significant changes in the ejection fraction.[141]

LIMITATIONS AND FUTURE DIRECTIONS

Speckle-derived strain is superior to tissue Doppler strain, particularly with regard to noise and angle dependency. However, the accuracy of speckle tracking is dependent on 2D image quality and frame rates. Low frame rates result in unstable speckle patterns, whereas high frame rates reduce scan-line density and reduce image resolution. Longitudinal strain data generally have been shown to have higher reproducibility than radial strain data.[17] The longitudinal displacement of the LV base may affect the speckle data obtained in short-axis views, particularly near the LV base, because of the presence of more through-plane motion. Moreover, lower lateral resolution often results in lateral dropout, and together with through-plane motion of the LV base, may account for wider variability of radial strain data. Technical developments in 3D speckle tracking with superior temporal and spatial resolution could theoretically circumvent the limitations of through-plane motion inherent in 2D imaging and provide a stronger scientific basis for resolving the different components of 3D strain tensor. A recent study by Nesser et al[142] compared 2-chamber and 4-chamber views using 2D and 3D speckle-tracking techniques. Though correlating well with cardiac magnetic resonance imaging, 2D STE was found to underestimate LV volumes with large biases in comparison with 3D STE. Another advantage of 3D speckle tracking is the evaluation of the motion of all myocardial segments in a single analysis step, which significantly reduces analysis time. Furthermore, assessment of LV rotational mechanics can be performed more accurately in one beat, in properly aligned anatomic planes with reduced geometric assumptions (Figure 7).

Ventricular remodeling and wall thinning of myocardial segments may affect the accuracy of strain measurements.[17] Nonuniform thickness and geometry of remodeled segments may result in variability in the region of interest during strain measurements, which in turn results in data variability. Strain on the segmental level has a relatively high standard deviation, and variations in lateral resolution of 2D echocardiography may cause variations in segmental strains in different walls of the left ventricle.[143] Global LV strain shows the lowest variability and is rapidly evolving as a robust variable for routine clinical application.

CONCLUSIONS

A growing body of evidence suggests that assessment of LV deformation by STE provides incremental information in clinical settings. Resolving the multidirectional components of LV deformation offers important insights into the transmural heterogeneity in myocardial contractile function that is useful for detecting subclinical states that are likely to progress into either systolic or diastolic heart failure. With the advent of 3D echocardiography, newer algorithms for tracking LV deformation hold promise for understanding the mechanisms of LV dysfunction and tracking the impact of novel therapies. One of the challenges looming is the rapid pace of technological growth, which has resulted in a great variety of software and algorithms. As STE becomes commonplace, it will be an important mission to ensure standardization of nomenclature, steps in data acquisition, and optimal training to reduce data variability.

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APPENDIX

A search of the Ovid Medline database was initially performed using 19 search terms to review cohort studies, case-control studies, cross-sectional studies, and systematic reviews published between January 2000 and November 2009. The results were then limited to the English language and human subject studies. The reference lists of retrieved articles were reviewed and separated into primary acquisition modality (DTI, speckle-tracking imaging, velocity vector imaging, automated functional imaging, strain echocardiography, MRI, and 2D strain imaging). All articles related to speckle tracking, automated functional imaging, velocity vector imaging, and 2D strain imaging were included in the present review. A hand review of the PubMed database was then performed using several search terms (*myocardial*, *cardiac*, *left ventricle*, *ventricle*, *infarction*, *ischemia*, *valvular*, *mitral*, *aortic*, *tricuspid*, *pulmonary*, *hypertension*, *regurgitation*, *stenosis*, *hypertrophy*, *cardiomyopathy*, *dilated*, *stress*, *pericardial*, *restrictive*, *congenital*, and *heart disease*) along with the PubMed and combined with "AND" with the following terms: *speckle*, *automated functional*, and *two-dimensional strain*. Articles identified in the PubMed search that were not identified in the initial Ovid Medline search were added to the database.