Strain: What Does This Add to Ventricular Function Assessment?

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Current practice

Transesophageal echocardiography (TEE) has advanced the role of the cardiovascular anesthesiologist and increased his/her active role and obligations during perioperative patient care. Assessment of global and regional left ventricular (LV) function consists of two-dimensional (2D) or Doppler evaluation of cardiac structures and their interaction with blood flow. The techniques used are mostly visual and subjective\(^\text{(1,2)}\) thus, not always accurate or error-free. Recent technological advances in signal processing in Doppler (Doppler tissue imaging [DTI] and Doppler strain echocardiography [DSE]) and non-Doppler (2D speckle tracking imaging [STE]) enable measurement of velocities, deformation and rotation. As a result, high quality, precise, and objective information regarding regional and/or global myocardial function (some of it in real time) decrease the subjectivity of the interpretation and increase the diagnostic accuracy.

The newer insight into myocardial structure has shown that myocardial fibers are organized in layers and form a leftward helix in epicardium, a rightward helix in endocardium and are circumferentially orientated in mid myocardium. The myocardial tissue is incompressible and the ventricular wall volume remains constant during the cardiac cycle. As a result, the afore-mentioned myocardial fiber arrangement results in longitudinal and circumferential thinning and radial thickening during systole, and opposite direction changes in diastole.\(^\text{(3)}\) During conventional TEE imaging, we evaluate only the inward motion (endocarial excursion) in either ME or TG views. However, both radial and longitudinal motions are important. It has been shown that in systole, a 40% radial thickening is accompanied by 14% longitudinal shortening.\(^\text{(4)}\) In addition, ischemia starts at the subendocardial level,\(^\text{(5)}\) which contributes to longitudinal myocardial motion.

Deformation

Strain means deformation.\(^\text{(6)}\) Myocardial strain (S or \(\varepsilon\), \%) is the deformation of a myocardial fiber, normalized to its original length (at the onset of the cardiac cycle):

\[
S = \frac{L_1 - L_0}{L_0} \times 100\%
\]

where \(L_0\) is the baseline (end-diastolic) length and \(L_1\) is the end-systolic length. By definition, strain is positive when two locations are moving apart (i.e., expansion) and negative when two locations move near (i.e., compression). Therefore, radial thickening is associated with positive strain (\(L_1 > L_0\)) while longitudinal shortening and circumferential thinning are associated with negative strain (\(L_1 < L_0\)). In echocardiography we measure Lagrangian strain, where \(L(t_o)\) is the end-diastolic shape with Doppler velocity gradients\(^\text{(7)}\) or non-Doppler speckle tracking.\(^\text{(8)}\)

Strain rate reflects how fast regional myocardial deformation occurs. The speed of this deformation is the strain rate (SR):

\[
SR = \frac{S}{t} \times \text{%/s}
\]

where \(t\) is the time duration of this deformation.
Strain measurements with either technique have been validated against sonomicrometry\(^8\) or magnetic resonance\(^9,11\) data, and correlate with each other (r values between 0.94 for strain rate and 0.96 for strain).\(^12\) In normal myocardium, SR reflects regional contractile function, being relatively independent of heart rate, whereas systolic S reflects changes in stroke volume.\(^13,14\) Evaluated with DTI or tagged cardiac MRI, all strains increased from base to apex and from endocardium to epicardium.\(^15,16,17\) Normal values are -16% - 24% (longitudinal strain), +48% (radial strain) and -20% (circumferential strain).\(^18,19,20\) Some have found significantly higher strain values in women than in men.\(^21\) Strain rate during isovolumic contraction showed good correlation with +dP/dt (r=0.74) and during isovolumic relaxation with –dP/dt (r=0.67).\(^22\) Strain is load dependent.\(^9,21\)

**Principles of DTI strain**

A shift in frequency is caused when transmitted ultrasound is reflected off a moving target (Doppler phenomenon). Modification of filter settings (reduction of gain amplification and bypass of the high-pass wall filter) will reject data from moving blood and permit recording of the stronger (approximately 40 dB higher amplitude) and slower velocity (< 25 cm/s) myocardial motion signal, respectively, thus enabling DTI. Doppler strain is obtained by placing a sample volume (usually 6×10 mm) over the myocardial area of interest while utilizing color DTI.\(^23\) The velocity gradient within this sample volume is used to calculate the deformation parameters SR and strain (by temporal integration of SR):\(^24\)

\[
SR = \frac{(V_2 - V_1)}{\sqrt{x}} \approx \frac{(_V)}{L_o} \approx \frac{(_L)}{t} \approx \frac{L_t}{L_o} \approx \frac{S}{t}
\]

A segment without velocity gradient does not deform and has a SR (and strain) of 0.

While not limited by tethering or translation effects, thus being superior to DTI velocities in the evaluation of regional myocardial function, it is time consuming and technically demanding to obtain DTI strain. The most important limitation arises from the fact that DTI is a Doppler technique (the angle between the Doppler and motion planes will underestimate the true myocardial velocity gradient if greater than 20°)\(^25\) and displays deformation along a single dimension only, that of the ultrasound plane. Because of this angle dependency, DTI is used primarily to assess longitudinal strain. Currently, DTI techniques are proprietary software and can analyze digitally stored images only from a same system.

**Principles of STE (2D) strain**

Scattering, reflection and interference of ultrasound with myocardium results in generation of a finely gray-shaded, speckled pattern. This speckled pattern is unique for each myocardial region and relatively stable throughout the cardiac cycle. The speckles function as acoustic markers, which are equally distributed within the myocardium and change their position from frame-to-frame in accordance with the surrounding myocardial deformation/tissue motion. The acoustic markers within a predefined region of interest are followed automatically frame by frame, and the change in their geometric position (which corresponds to local tissue movement) is used to extract strain and strain rate. Because these acoustic markers can be followed in any direction, non-Doppler stain is an angle independent technique for calculation of cardiac deformation. Therefore, radial and longitudinal deformation can be measured in the ME views, and radial and circumferential deformation in the SAX views.\(^26\) The reproducibility of strain measurements is reported to be <15%.\(^27\)

**Shear Strain and Torsion**

The left-handed oriented epicardial fibers and right-handed oriented endocardial fibers produce shear strain during the cardiac cycle (deformation parallel to the reference plane). This results in the base and the apex of the heart rotating in opposite directions. From a TEE perspective, the base rotates clockwise (preceded by an early systolic counterclockwise rotation) and the apex counterclockwise (preceded by an early systolic clockwise rotation), producing torsion of the ventricle (the difference in apical and basal rotation), similar to wringing a towel dry.\(^4\) As a result, during the cardiac cycle there is a systolic twist and an early diastolic untwist of the LV along its long axis. Rotation angles and torsion can be measured with STE\(^28,29\) and measurements correlate well with sonomicrometry and tagged MRI. The difference between basal and apical rotations is torsion (twist). LV torsion occurs mainly by the counterclockwise apical rotation and links systolic and diastolic function: systolic twisting stores elastic energy which is released during the isovolumic phase of diastole, and untwisting generates intraventricular pressure gradients allowing LV filling to proceed at low filling pressure.\(^4\) In healthy subjects during systole, the torsion increases and the LV volume decreases, but during diastole, the relation between rapid untwisting (uncoiling) and
increasing volume is non-linear. Initiation of untwisting is an early and key mechanism that promotes early diastolic relaxation and early diastolic filling, possibly more important than recoil of systolic basal descent. Patients with HCM showed delayed untwisting that was not significantly augmented with exercise. That explains their inability to increase filling during exercise without a significant increase in left atrial pressure.

**Correlation between DTI-strain and STE-strain**

Either DTI or STE technique measures deformation accurately, in normal subjects as well as patients. Using receiver-operating characteristic curve, STE showed greater area under the curve to discriminate among dysfunctional segments than DTI strain. Contrary to DTI, STE depends on image quality. Poor imaging will result in decreased speckled appearance and poor tracking of the myocardium.

**Applications of DTI- and STE-derived strain**

DTI-derived strain accurately measures cardiac deformation, sensitive to early ischemia and is useful in assessing myocardial viability after myocardial infarction better than DTI-velocities or wall motion scoring. DTI-strain in remote from ischemia regions will remain normal, contrary to DTI velocities, which are affected due to tethering.

**Normal vs abnormal, global values**

Using STI, global longitudinal strain <-21% (normal: -24.1 +/- 2.9%) and global longitudinal SR <-0.9/s (normal: -1.02 +/- 0.09/s) had good sensitivity and specificity (92% and 89%, and 92% and 96% respectively) for the detection of post-MI patients (n=27). There was a good linear correlation between the wall-motion score index and the GLS and GLSR.

**Ischemia detection**

Doppler strain may be an important supplement to visual assessment (WMS) of regional LV dysfunction, superior to DTI velocities. In 17 patients with LAD disease (>75% obstruction) and normal baseline EF and WMS, DTI strain detected systolic longitudinal expansion in apical segments (baseline -17.7±7.2% vs +7.5±6.5%) or reduced compression in mid septal segment (baseline -21.8±8.2% vs -13.1±4.1%) in nearly all patients during balloon occlusion of LAD. Segments not supplied by LAD remained unchanged.

DTI strain indexes differentiate acutely ischemic myocardium from normal and dysfunctional myocardium, even in segments with normal WMS. In a population of 90 consecutive coronary artery patients with >90% occluded vessel who underwent balloon PTCA, baseline strain values in the at-risk segments with normal WMS were similar to those observed in control patients (radial: 49±6.9% vs 56.3±11.7%, longitudinal: -21.2±4.5% vs -23.3±4.7%). At-risk segments with abnormal WMS had decreased strain values (radial: 21.9±11% , longitudinal: -5.2±4.5%) and increased relative postsystolic deformation (PSI) (radial: 0.18±0.14, longitudinal: 0.32±0.26) as compared to normal and at-risk segments with normal WMS. Coronary occlusion resulted in a 50% reduction of radial and longitudinal strain, which peaked early in diastole, and increase PSI in all at-risk segments (with and without abnormal WMS). These changes were reversible, and after 2 minutes of coronary reperfusion, segmental deformation parameters returned to pre-occlusion state. Neighboring segments did not exhibit any changes, and presence of collaterals diminished the occlusion-associated strain parameter changes (less post-systolic strain and lower PSI). PSI appeared the most accurate parameter in differentiating acutely ischemic segments during coronary occlusion from baseline normal and abnormal segments with 92% sensitivity and 95% specificity.

STI derived circumferential and radial strain is sensitive to acute reduction of myocardial perfusion. During balloon occlusion, there was a significant decrease in circumferential strain (baseline -18.5±7.2% to -10.5±3.8%) and radial strain (baseline 46.5±19.4% to 35.7±20.8%) and prolongation of the time to peak circumferential and radial strain.

**Regional function, normal vs abnormal**

Systolic DTI strain and SR but not myocardial velocities can accurately differentiate abnormally from normally contracting segments. Longitudinal deformation is potentially superior to visual WMS in the quantification and identification of subtle ischemia-induced changes in regional contractility. When correlated with coronary angiogram, DTI strain was significantly reduced in normokinetic segments supplied by a stenosed coronary artery (>70%) but not in normokinetic segments supplied by a coronary artery without significant lumen narrowing.
DTI radial SR agrees well with wall motion, and is significantly reduced in hypokinetic and akinetic segments but not in normokinetic segments. SR reflects changes in WMS induced by dobutamine challenge: it increased in those segments which revealed augmented wall motion and decreased in those segments which showed deteriorating or unchanged wall motion. (40)

Radial and circumferential STI strain enable distinction between normokinetic, hypokinetic and akinetic segments at rest (defined by cMRI), in a highly reproducible manner and with small intra- and interobserver variability. (41) A cut-off value of radial strain <29% defined hypo- from normokinetic segments with sensitivity and specificity of 83%, and a cut-off value of radial strain <21% akinetic from hypokinetic segments with sensitivity of 83% and specificity of 94%.

Similar discriminatory ability of STI radial strain was found when transmurality of myocardial infarction was analyzed using contrast-enhanced cardiac MRI. Non-transmural infarction was distinguished from transmural infarction segments by radial strain cut-off value of >16.5%. (42)

The use of STI strain for combined assessment of long- and short-axis cardiac function may allow differentiation of transmurality of chronic infarction and therefore, overcome the limitations of DTI strain, which is angle limited and can evaluate only longitudinal function. In subendocardial infarction, STI radial and circumferential strain are preserved, while longitudinal strain is reduced. In contrast, in transmural infarcts both short-axis and long-axis STI strain are significantly reduced. (43)

Recovery
Accurate identification of non-viable myocardium from viable but hypokinetic segments has important clinical implications, because revascularization benefits only patients with a sufficient amount of viable myocardium while it is unlikely to benefit those with transmurally infarcted myocardium.

In post-MI patients, and in contrast to myocardial velocities, longitudinal DTI SR of transmural infarcted segments was significantly decreased when compared with non-transmural and normal segments. (44) STI radial strain is able to identify myocardial dysfunction and predict recovery of function using a cut-off value of peak radial strain >17.2%. (45)

Strain in the operating room
TEE measurements of DTI strain are comparable with transthoracic assessment and pericardiotomy does not affect them. (46) DTI strain was found to be superior to myocardial velocity measurements in detecting and assessing regional myocardial ischemia during off-pump LAD revascularization. DTI strain demonstrated systolic lengthening of the apical septum and reduced longitudinal shortening of the mid septum during interrupted LAD flow. These changes occurred with concomitant deterioration of wall motion, and were confined in the LAD territory, while there were no changes in the basal septum, supplied by the right coronary artery. (47) At the same time, DTI velocities remained unchanged in the apical septum during interrupted LAD flow, probably explained by traction from the basal segments.

Rotation and twist
Estimation of LV twist from apical rotation is simple. Apical rotation, measured by STE (12.2±3.8°) represents the dominant contribution to LV twist and correlates to LV twist over a wide range of hemodynamic conditions, making it a non-invasive, feasible clinical index of LV twist. (31) In patients with chronic ischemia but preserved LVEF, rotation and twist were similar to healthy subjects, but in those with depressed LVEF, apical rotation and twist were reduced. (31) Systolic twist was depressed and diastolic untwisting prolonged in patients with anterior wall MI and abnormal LV systolic function. These abnormalities were related to reduced apical rotation and associated with the reduction of apical circumferential strain. (48) In contrast, systolic twist was maintained in patients with anterior wall MI and LVEF >45%. This is a result of the mild reduction of circumferential strain in the apex that may affect LV twist behavior in mild manner. In patients with diastolic dysfunction (DTI E’ <8 cm/s) peak LV twist is increased in early-stage diastolic dysfunction, mainly because of more vigorous and increased LV apical rotation. (49)

Conclusion
Imaging of cardiac deformation offers a new insight into regional and global myocardial function. However, like any ultrasound modality, both DTI and STE depend on image quality, are time-consuming and technically demanding for the novice operator. Although not part of the mainstream echocardiographic examination, introduction of deformation and rotation parameters in the everyday clinical practice will for sure offer a lot in the objective quantification of left and right ventricular function.
References

7. Marwick TH. Heart. 2003;89:1377-1378
30. Foster E and Lease KE. J Am Coll Cardiol. 2006;113:2477-2479
42. Becker M et al. Eur Heart J. 2006;27:2560-2566