TISSUE DOPPLER/STRAIN/SPECKLE

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At the conclusion of these lectures, the participant should be able to:
1. Describe the current limitations of imaging modalities to determine myocardial structure and function
2. State why and how Tissue Doppler imaging is used
3. Define the rationale for strain assessment in a complete echocardiographic assessment
4. Describe the method for using Strain in a complete echocardiographic assessment

Anatomic and physiologic background – The LV longitudinal motion

Conventional TEE images LV cardiac motion along two axes: the long axis along which the myocardium shortens (the mitral annulus [MA] descends towards the relatively stationary apex), and short (or transverse) axis, along which the myocardium thickens. At the same time, base and apex rotate in opposite directions (appreciated only in the basal TG views). The anatomic background of this three-dimensional motion lies in the myocardial architecture: epicardium and subendocardium have longitudinal fibers (from the base to the apex from a TEE perspective, the epicardium is twisting in a clockwise orientation, and the subendocardium is twisting in a counter-clockwise orientation), while mid-myocardium contains circumferential fibers. The normal right ventricular (RV) wall has mostly longitudinally oriented fibers. Since muscle is incompressible, longitudinal deformation of myocardium will correspond inversely to changes in radial thickness. Therefore, monitoring the heart motion along the three axes has the potential to offer valuable information about heart function. This is the basis of Doppler tissue imaging (DTI) and strain echocardiography.
Doppler Tissue Imaging

Myocardial velocity: Principles of Doppler tissue imaging (DTI)

Conventional Doppler records blood flow velocity. DTI records myocardial velocity. Tissue motion creates Doppler shifts that are stronger (approximately 40 dB higher in amplitude) and significantly slower (velocity <25 cm/s) than those from blood flow. Modifications (reducing gain amplification and bypassing the high-pass wall filters) enable DTI. DTI requires a high frame (>100 FPS), and using a narrow image sector and selecting the appropriate velocity scale enables this. With DTI, myocardial velocities, displacement and myocardial deformation are measured.

DTI modalities and measurements

As with conventional Doppler, there is spectral and color displays of DTI. When evaluating diastolic function, DTI recordings are mostly done lateral to the mitral annulus from a 2-5 mm sample volume. It is important that the myocardial area of interest is placed in the center of the ultrasound beam for parallel alignment of motion plane with the cursor. The Nyquist limit should be <20-30 cm/s, with minimum gain and low wall filter settings, and the sweep speed should be set at 50-100 mm/s. DTI is done with either spectral (pulsed-wave) or color Doppler.

Limitations of DTI are: (i) inability to differentiate between actively contracting and passively drawn tissue (tethering), (ii) inability to analyze separately the different myocardial layers (i.e., sub- from epicardium), and (iii) angle-dependency of Doppler velocities.

<table>
<thead>
<tr>
<th>Doppler Tissue Imaging</th>
<th>Mode</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; measurement</th>
<th>2&lt;sup&gt;nd&lt;/sup&gt; measurement</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt; measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PWD</td>
<td>Peak velocity</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Color Doppler</td>
<td>Mean velocity ⇒</td>
<td>Displacement</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity gradients ⇒</td>
<td>Strain rate ⇒</td>
<td>Strain</td>
</tr>
</tbody>
</table>

Spectral DTI provides on-line measurements of peak myocardial velocities and time intervals with excellent temporal resolution. DTI velocities can be recorded with TEE from the following walls: (i) all basal segments in the ME LV views, (ii) right ventricular (RV) free wall lateral to tricuspid annulus (inflow part of the RV), in the ME 4C or modified deep TG RV LAX view at ~130°, and (iii) RV outflow tract at the level of the pulmonic valve, in the modified deep TG RV LAX view at ~70°.
Spectral DTI in “older” echocardiographic systems
An older echocardiographic system may not be equipped with a default “DTI” function; however, proper manipulation of the conventional Doppler settings allows a rudimentary DTI function. Positioning a basal LV segment (ME views) so that the longitudinal motion is as parallel to the Doppler beam will allow recording of myocardial velocities if: a small sample volume (5 mm) is used, the Doppler gain is decreased to the minimum, the scale is reduced to ±15 cm/s and the low velocity filter is cancelled.

DTI velocities are positive if moving toward, and negative if moving away from the transducer. The DTI velocity signal has 3 main components: one systolic (S') and two diastolic, early (E') and late (A'). The diastolic velocities are similar in appearance and timing to the TMF velocities. The late (A') diastolic velocity may not be evident in atrial fibrillation or tachycardia. An isovolumic relaxation (IR) velocity can be seen before the E'. Clinical measurements include peak velocities (cm/s) and the ratio E'/A' (%). When recorded from the MA, the velocities receive the subscript “a”, i.e., Sa, Ea, Aa.

Doppler Tissue Imaging: E'

DTI recordings. (A): Spectral display of peak systolic (S'), early (E') and late (A') diastolic velocities and isovolumic contraction (IC) and relaxation (IR) velocities, recorded “live”. (B): Spectral display of mean velocities, extracted off-line, from sample volumes positioned within the basal inferolateral LV segment (ME 4C view). Notice the velocity gradient: the more basal region (yellow sample volume) has a higher velocity than a more apically located (green sample volume).

Limitations of spectral DTI velocities are: (i) influenced by cardiac translation but not pericardiotomy; when recorded from the LV base, lateral to the MA, these influences are minimized, (ii) heterogeneous: S’ is higher in the LV basal than in the mid or apical segments, and in lateral and inferior than anterior or septal segments; E’ is greater at the base than in the mid LV, while A’ has a more uniform distribution, (iii) decreasing with aging.
DTI spectral recordings from ME basal LV segments. White sample volumes mean unfavorable alignment between Doppler beam and direction of motion of respective basal segment.

Normal values for spectral DTI velocities (cm/s ± 1 SD) for the basal segments of the LV in awake patients are shown in below. Peak systolic velocity at the MA should be approximately >6 cm/s, and displacement should be >10 mm.

<table>
<thead>
<tr>
<th></th>
<th>S'</th>
<th>E'</th>
<th>A'</th>
<th>E'/A'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral</td>
<td>10.6 ± 2.3</td>
<td>13.3 ± 3.3</td>
<td>11.3 ± 2.9</td>
<td>1.5 ± 0.6</td>
</tr>
<tr>
<td>Septal</td>
<td>9.9 ± 1.7</td>
<td>11.5 ± 2.6</td>
<td>9.5 ± 2.4</td>
<td>1.0 ± 0.7</td>
</tr>
<tr>
<td>Anterior</td>
<td>9.2 ± 1.8</td>
<td>11.7 ± 3.4</td>
<td>10.3 ± 2.9</td>
<td>1.2 ± 0.7</td>
</tr>
<tr>
<td>Inferior</td>
<td>10.4 ± 2.5</td>
<td>14.3 ± 3.6</td>
<td>11.6 ± 2.6</td>
<td>1.3 ± 0.7</td>
</tr>
</tbody>
</table>

In color DTI, velocities are displayed as a parametric color image (a color Doppler map superimposed on 2D image) and each pixel represents velocity, encoded with red if moving toward, and blue if moving away from the transducer. Images are digitally acquired and stored, and mean myocardial velocities are extracted off-line. As such, the color DTI velocities are on average 25% lower than the spectral DTI velocities. Different myocardial layers can be separately analyzed, since the sample volume is positioned post-processing anywhere inside the myocardium. Conventional or anatomically curved M-mode color DTI provides adequate temporal resolution (10-100 ms) to analyze cardiac events, and display segmental asynchrony between different myocardial segments (i.e., basal vs mid vs apical).

Applications of DTI

-Grading of diastolic function and estimation of filling pressures

The DTI E’ velocity is related to LV relaxation and elastic recoil and correlates inversely with peak negative dP/dt and LV end-systolic volumes. E’ is higher in lateral and inferior segments than in anterior and septal ones, and a value >12.5 cm/s is associated with normal diastolic function, particularly when measured
during a Valsalva maneuver. Compared to the load-dependent TMF E-wave, E’ at the lateral LV base is relatively preload independent, particularly if systolic function is impaired. Therefore, the effects of preload on LV filling can be corrected by the ratio of TMF-E/DTI-E’, and reveal underlying relaxation abnormalities. The diastolic function is abnormal if E/E’ >10; this can be utilized to further characterize the patient with "pseudonormal" TMF filling pattern (E/A >1): it is normal only if the DTI ratio E’/A’ >1 and pseudonormal if DTI ratio E’/A’ <1. A ratio E/E’ >10 is associated with pulmonary capillary wedge pressure >15 mmHg (mean capillary wedge pressure = 1.9 + (1.24 × E/E’). A ratio E/Em >15 was highly specific for elevated, and E/E’ <8 was highly sensitive for normal left atrial pressures.

- **Ischemia detection:**
Coronary disease is echocardiographically evaluated by visual analysis of regional wall motion abnormalities (RWMA), which is based on the detection of changes in the radial motion and systolic thickening. The qualitative evaluation of RWMA is unable to resolve short delays in regional contraction and may fail to identify ischemia-induced myocardial dysfunction. Ischemic changes occur earlier in the longitudinal than the transverse/radial axis. In an animal model, a significant reduction of S’ and an early decrease of E’/A’ were detected within 5 s of acute occlusion of the left anterior descending artery. An additional systolic velocity can be seen with DTI once ischemia develops, that continues during the early phase of systole. In the ME views, this is called post-systolic shortening (PSS). It is associated with viability of the myocardial segment. Patients with myocardial infarct tend to have significantly reduced S’ in the non-infarcted walls as well. Non-ischemic segments have an E’/A’ >1. E’ is reduced in the infarction sites, and is affected by ischemia more than A’, even in the presence of intact systolic function. An E’/A’ <1 is sensitive for ischemia, and is found in akinetic and hypokinetic segments. The DTI E’/A’ ratio is dimensionless and particularly helpful, because it is not Doppler-angle dependent.

- **Heart disease:**
Chronic volume overload influences E’. Patients with mitral regurgitation may have higher E’ velocities than patients with aortic regurgitation. In heart failure patients, DTI can offer important prognostic information: in a 2-year follow-up of 518 patients (165 normal), S’ ≤3 cm/s, E’ ≤3 cm/s, A’ ≤4 cm/s, and E/E’ >20 independently identified those at risk of cardiac death.

-Utility of DTI E’/A’ ratio in the operating room
There are no normal values for DTI parameters in anesthetized patients. The preload dependence of E’ is high, particularly if systolic function is normal; no single E’ value should be used to characterize the diastolic state in anesthetized, mechanically ventilated patients. Instead, the DTI ratio E’/A’ should be used, since the ratio is dimensionless and any Doppler angle effect is decreased. A DTI E’/A’ >1 is considered normal for the myocardial wall segment. For global estimates, the average E’/A’ ratio, sampled from inferoseptal, anterolateral,
inferior and inferolateral basal segments should be taken into account. Inversion of an E’/A’ ratio (<1) in the absence of significant volume changes signifies development of regional, subendocardial ischemia, until proven otherwise. A Valsalva maneuver should be tried whenever an E’/A’ ratio >1 is encountered: reversal of the ratio means volume dependence of E’.

The ratio TMF-E/DTI-E’ should be reliably used for estimation of filling pressures in cases with LVEF <50%. Instead of a single E’ value, the average from different basal segments should be used. For both E and E’ velocities, minimizing the Doppler angle are of paramount importance. The Doppler angle can be optimized (minimized) by manipulating the image, so that the longitudinal motion is as parallel as possible with the Doppler beam.

### Diastolic function: intraop evaluation

<table>
<thead>
<tr>
<th></th>
<th>I. Impaired relaxation</th>
<th>II. Pseudonormal pattern</th>
<th>III. Restriction</th>
</tr>
</thead>
<tbody>
<tr>
<td>E/A</td>
<td>&lt;0.8</td>
<td>0.8 – 1.5</td>
<td>≥2</td>
</tr>
<tr>
<td>DT (ms)</td>
<td>&gt;200</td>
<td>160 – 200</td>
<td>&lt;160</td>
</tr>
<tr>
<td>Mean E/E’</td>
<td>≤8</td>
<td>8 – 12</td>
<td>≥13</td>
</tr>
<tr>
<td>rA – A (ms)</td>
<td>0</td>
<td>≥30</td>
<td>≥30</td>
</tr>
<tr>
<td>Valsalva ∆E/A</td>
<td>&lt;0.5</td>
<td>≥0.5</td>
<td>≥0.5</td>
</tr>
</tbody>
</table>

E: early TMF; A, late TMF; DT, deceleration time of TMF-E; E’, early DTI diastolic velocity; rA, reversal PVF atrial wave
Strain and Strain Rate: The study of myocardial deformation

Many of the limitations related to DTI are overcome by assessing myocardial strain instead. **Strain** ($\varepsilon$, %) is the deformation of an object after application of force (stress), normalized to its original shape (or length, $L_o$): $\varepsilon = \frac{L - L_o}{L_o}$. In a one-dimensional object, the only possible deformation is shortening (negative $\varepsilon$) and lengthening (positive $\varepsilon$).

**Deformation (strain):** $\varepsilon = \frac{L - L_o}{L_o}$

$L_o$ initial length  
$L$ length after deformation

**Strain is dimensionless:**  
% change from resting state ($L_o$)

**Strain Rate** = Strain / time (sec$^{-1}$)
An example of one-dimensional ε is wall thickening (WT), measured in the anterior or inferior wall segment in the TG SAX view: %WT = (LED – LES) / LED. For a 2D object, deformation occurs along both the x axis and y axis (normal strain: the motion is normal to the borders of the object), and parallel to the borders of the object (shear strain). For a 3D object, such as a myocardial segment, there are three normal strains (along the x, y, z axes), and six shear strains (along the axes combinations). During ventricular contraction, negative ε will be recorded from myocardial shortening in the longitudinal and circumferential dimensions (with the cursor lined up with the heart long axis), and positive ε from myocardial thickening in the radial direction (with the cursor lined up with the short axis).

**Strain Rate (SR, Ŝ, s⁻¹)** is the speed of deformation. If an object had a 30% total deformation over 2 sec, then SR is 0.30/2 = 0.15 s⁻¹ (the object lengthens by 15% every sec). In most biological tissues the relationship between stress and strain is not linear.

**Rotation** (degrees) of the LV base and apex occur because of the helical orientation of the myocardial fibers: the apex rotates counterclockwise and the base clockwise (from a TEE perspective, i.e., base to apex). The mid-LV is usually stationary. These opposite motions lead to the LV twisting in systole and untwisting in diastole. The LV **twist** is the apex-to-base difference of LV rotation. **Torsion** is the base-to-apex gradient in the rotation along the LV long axis (degrees/cm).

Strain represents myocardial shortening and lengthening, while DTI measure motion velocity relative to the transducer. Beware that both are regional measurements, however, SR and ε are less sensitive to segment tethering and cardiac translation. Myocardial deformation is the result of the complex interaction of intrinsic contractile force and extrinsic loading conditions applied to a tissue with viable elastic properties. Changes in preload, afterload and myocardial stiffness are important determinants of the pattern and magnitude of myocardial deformation. Strain will increase with volume infusion while contractility does not change. The echocardiographic strain has been validated with mechanical strain, measured with sonomicrometry and magnetic resonance imaging and has been shown to correlate very well with contractility. Myocardial deformation can be measured in the radial (transmural, basal and mid, inferior and anterior segments in the TG SAX view, and basal and mid anterior and inferior segments in the TG 2C view), in the longitudinal (all six walls using ME views), and in the circumferential (septal and lateral segments in the TG SAX view) directions. SR is age-dependent. Longitudinal SRs are relatively heterogeneously distributed from base to apex, and are approximately half of radial SRs. A transmural gradient exists in normal myocardium, with higher SRs in the subendocardial layer. The RV free wall has higher SR than LV.

Normal values (in the same segment): longitudinal ε: -25 ± 7% (range: 15%-25%), radial ε: -57 ± 11% (range: 50%-70%). Strain values > -14% should be
considered pathological. Normal values: longitudinal SR: \(-1.9 \pm 0.7 \text{ s}^{-1}\), radial SR: \(-3.7 \pm 0.9 \text{ s}^{-1}\).

**Echocardiographic techniques for measurement of SR and \(\varepsilon\)**
- **Doppler (DTI):** if \(L\) in the strain equation is divided by \((t)\), then SR can be calculated from velocities \((v)\): \(\text{SR} = \frac{[v - v_0]}{v_0}\). The velocity of myocardial motion is recorded by color DTI techniques, and SR (the spatial gradient of velocities) and \(\varepsilon\) (time integration of SR) are calculated.

- **Two-dimensional (STI, speckle tracking imaging):** this technique is not based on Doppler. Myocardial deformation is determined from continuous frame-by-frame tracking of a small block of speckles ("acoustic markers"). The appearance of these markers is considered to be relatively stable between subsequent image frames, and a change in their position is assumed to follow tissue motion. STI \(\varepsilon\) and SR are calculated from the displacement and rate of displacement of each marker. With STI, the global (longitudinal and circumferential) deformation can be automatically measured, has better spatial resolution but requires a low frame rate (~60 per sec). With STI, the longitudinal \(\varepsilon\) has a better correlation with sonomicrometry than circumferential \(\varepsilon\). Normal values for STI strain is slightly lower than DTI strain: \(-18.6\pm0.1\%\) in healthy individuals, compared to DTI (-22.9%, confidence intervals -17% to -29%).
Limitations of DTI and STI measurements
- **Noise**: Measurement of SR is prone to noise. A 5- to 10-mm sample volume is a reasonable trade-off between high spatial resolution and low noise. STI is less prone to noise compared to DTI ε and SR.
- **Doppler-dependency**: All DTI measurements (but not STI) are limited by the Doppler angle. In clinical practice, this angle dependency does not probably have an effect on the timing of specific events or on the profile of the curves. To improve accuracy a frame rate of >100 frames/s is required.
- **Optimal tissue visualization**: No strain is recorded by either technique if tissue is not visualized. STI requires the imaging of all myocardial layers. For DTI, recordings should be done with second harmonic imaging to optimize tissue visualization.
- **DTI**: Longitudinal and circumferential deformations have opposite signs than radial deformation, and deviation from one direction to another will consequently affect SR values measured with DTI. Furthermore, measurements are done along a single ultrasound scan axis/dimension, and provide only one-dimensional estimate of myocardial deformation, even when the sample volume is “anchored” within a segment. Not all strain components (radial, longitudinal and circumferential) can be measured in all LV segments with DTI or STI.

Clinical applications of strain echocardiography
- **Global longitudinal strain**
It is the average of the regional strain values from all ME LV views. It can be calculated in a semi-automated fashion in systems with the preset function. Not yet explored in clinical areas, it may provide an easy-to-acquire clinical measurement for the quantification of global (and regional) systolic LV function. In coronary artery disease, regional longitudinal strain values >-15% and
circumferential >-11% reflect decreased function. Similar to DTI post-systolic velocity, the development of post-systolic strain and its ratio to maximal strain may be used to mark ischemia during dobutamine stress echocardiography, if $\varepsilon_{\text{pss}}/\varepsilon_{\text{max}} > 35\%$.

- **Diastolic function**
  Differences in SR during the initial phases of diastole appear to identify early changes in regional myocardial function (in the absence of systolic and gross morphological changes). Regional abnormalities in diastolic function (which may indicate the presence of regional disease or may be caused by aging) are shown by changes in DTI-E’ (impaired relaxation) and regional $\varepsilon$ curves (changes in compliance).

- **Cardiac synchronization therapy (CRT)**
  Appropriate CRT can acutely improve regional SR and reduce the regional delay between QRS onset and peak $\varepsilon$, even without changes in systolic DTI velocities.

- **Rotation and twist**
  Estimation of LV twist from apical rotation is simple. The apical rotation is and STI measurement (12.2±3.8°) and represents the dominant contribution to LV twist making it a non-invasive, feasible clinical index of LV twist. In patients with chronic ischemia but preserved LV ejection fraction, rotation and twist were similar to healthy subjects, but in those with depressed LV ejection fraction, apical rotation and twist were reduced. Systolic twist was depressed and diastolic untwisting prolonged in patients with anterior wall myocardial infarction and abnormal LV systolic function. These abnormalities were related to reduced apical rotation and associated with the reduction of apical circumferential strain. In contrast, systolic twist was maintained in patients with anterior wall myocardial infarction and LV ejection fraction >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.

**References:**
Edvardsen T and Haugaa KH. Imaging assessment of ventricular mechanics. Heart 2011;97:1349-56
Gjesdal O, et al. Noninvasive separation of large, medium, and small myocardial infarcts in survivors of reperfused ST-elevation myocardial infarction: a
Greenberg NL, et al. Doppler-derived myocardial systolic strain is a strong index of left ventricular contractility. Circulation 2002;105:99-105
Isaaz K. Tissue Doppler imaging for the assessment of left ventricular systolic and diastolic functions. Curr Opin Cardiol 2002;17:431-42
Pellerin D, et al. Tissue Doppler, strain and strain rate echocardiography for the assessment of left and right systolic ventricular function. Heart 2003;89(Suppl III):iii9-iii17
Skubas NJ. Intraoperative Doppler Tissue Imaging is a Valuable Addition to Cardiac Anesthesiologists’ Armamentarium: A Core Review. Anesthesia and Analgesia 2009;108:48-66
Skubas NJ. Two-dimensional, non-Doppler strain imaging during anesthesia and cardiac surgery. Echocardiography 2009;26:345-53
Thomas G. Tissue Doppler echocardiography – A case of right tool, wrong use. Cardiovascular Ultrasound 2004;2:12
Thomas JD and Popovic ZB. Assessment of left ventricular function by cardiac ultrasound. J Am Coll Cardiol 2006;48:2012-25
