LEFT VENTRICULAR: ASSESSMENT OF SYSTOLIC FUNCTION

ECHOWEEK 2015

Mark A. Taylor, MD, FASE
Allegheny Health Network
Temple School of Medicine
Pittsburgh, PA

Learning Objectives:
1. Describe the normal LV anatomy and function using 2D ultrasound and Doppler.
2. Identify systolic LV pathology using 2D ultrasound and Doppler.
3. Recognize the echocardiographic manifestations of regional LV systolic dysfunction.

Definitions:
TEE-Transesophageal Echocardiography
TTE-Transthoracic Echocardiography
LV-Left Ventricle
RV-Right Ventricle
ME-Midesophageal
TG-Transgastric
SAX-short axis
LAX-long axis
LVID-Left Ventricle Internal Diameter
PWT-Inferolateral Wall Thickness
SWT-Septal Wall Thickness
EF-Ejection Fraction

Introduction
Assessment of left ventricular systolic function is an important component of a comprehensive echocardiographic examination. Evaluation of global and regional left ventricular performance is accomplished by assessing contractile function and the size and shape of the ventricle. Qualitative methods with visual estimation of ejection fraction and quantitative methods with measured chamber volumes and calculated values are useful to determine left ventricular function, the degree of systolic dysfunction and assess possible etiologies and treatment strategies. Ventricular function assessments are most commonly performed by TTE and normative values for TEE are still undetermined. Three-dimensional and simultaneous multiplane image acquisition are recent advances in TEE that allow qualitative and quantitative evaluation of LV function with TEE. Qualitative assessment of LV size and function has significant inter observer variability and is related to interpreter skill level. It is recommended to compare qualitative assessments to quantitative measures to provide a cross reference on both methods of assessment.

Echocardiographic Assessment of Global Left Ventricular Function
In order to maximize image acquisition and measurements for 2-dimensional and 3-dimensional quantification the following elements should be considered:

- Image at minimum depth necessary
- Utilize the highest frequency transducer
- Adjust gain, dynamic range, transmit, focal zone and lateral gain appropriately
- Frame rate greater than or equal to 30/s
- Harmonic imaging
- B-color imaging
- Avoid apical foreshortening
- Consider use of contrast enhancement
- Identify end diastole and end systole by mitral valve and aortic valve motion and cavity size rather than reliance on ECG.

Ventricular systolic function is most commonly assessed by "load dependent" indices due to their ease of clinical applicability. These measurements are highly subject to changes in preload and/or afterload and should be utilized with consideration of current loading conditions, including anesthetic effects.

Echocardiography can be utilized to qualitatively and semiquantitatively assess preload and reflects the volume at the end of diastole. Left ventricular end diastolic area (EDA) may serve as a surrogate for preload. Studies in patients undergoing graded hypovolemia, in both pediatric and adult populations demonstrate changes in LVEDA obtained in the transgastric midpapillary short axis (TG midpap SAX) view, which correlate to changes in volume status.

\[
\text{EDA index (cm}^2/\text{m}^2) = \frac{\text{LVEDA}}{\text{BMI}}
\]

An EDA indexed to BSA less than 5.5 cm²/m² defines hypovolemia. A decrease left ventricular end systolic area (ESA) or end-systolic cavity obliteration can suggest hypovolemia but has low specificity for predicting a decrease in preload. In addition to hypovolemia, an increase in ejection fraction or a decrease in systemic vascular resistance can lead to end systolic cavity obliteration.

Wall stress can be utilized to measure myocardial function and reflects the balance of forces acting upon the left ventricular wall during systole. Left ventricular wall stress depends on chamber size, myocardial thickness, intraventricular pressure and ventricular configuration. Wall stress includes circumferential (short axis), radial (intracavitary), and meridional (long axis). Afterload can be measured by echocardiography but this is rarely performed by TEE in the perioperative setting.

Meridional wall stress, which acts upon the longitudinal axis of the LV, can be calculated by the following equations:

\[
\partial_m \text{ (dynes/cm}^2) = 1.35 \times \frac{P(\text{LVID})}{4h(1+h/LVID)}
\]

\[
\partial_m = \text{end-systolic meridional wall stress}
\]
\[
P = \text{pressure in the LV at the end of systole (may substitute SBP)}
\]
\[
\text{LVID}=\text{LV internal diameter}
\]
\[
h=\text{end-systolic inferior wall thickness}
\]

OR

\[
\partial_m \text{ (dynes/cm}^2) = 1.33 \times \left\{BP_{\text{sys}}(A_m/A_c)\right\} \times 10^3
\]
\[ \sigma_m \] = end-systolic meridional wall stress
\[ A_c \] = LV cavity area in the short axis view
\[ A_m \] = myocardial area
\[ BP_{sys} \] = systolic blood pressure

Standard 2D and 3D TEE imaging planes to quantify global and segmental left ventricular function include:

**ME 5-Chamber** (true apex not visualized and therefore caution must be exercised in assessing global and regional LV systolic function)

**ME 4-Chamber** (infereoseptal and anterolateral LV segments, lateral RV wall)

**ME Mitral Commissural** (anterior/anteralateral and inferior/inferolateral LV segments)

**ME 2-Chamber** (anterior and inferior LV segments)

**ME LAX** (inferolateral and anterior septal LV segments)

**TG Midpapillary SAX** (6 LV segments)

**TG Basal SAX** (6 LV segments)

**TG Apical SAX** (4 LV segments)

**TG LAX** (inferolateral and anterior septal LV segments)

**TG 2-Chamber** (anterior and inferior LV segments)

Measurements should occur in the TG mid-LV SAX, TG LV 2-chamber, or TG LV LAX view. Diameter measurements should be perpendicular to the long axis of the LV so the TG LV 2-chamber or TG LV LAX should be utilized. Recommended measurement locations differ for TTE (MV tip) versus TEE (closer to mid LV). Measurements should be made over several beats with an average of 3 for normal sinus rhythm and a minimum of 5 beats for atrial fibrillation.

Common “load dependent” echocardiographic techniques to assess global LV function include:

1. **Measurement of left ventricular end-diastolic diameter (EDD) and End-systolic diameter (ESD).**
   a. Imaging planes
      i. Parasternal short axis image (TTE)
      ii. TG Mid Papillary SAX view (TEE)
         1. Use of simultaneous multiplane imaging helps ensure on-axis measurement, perpendicular to the long axis of the LV.
      iii. TG 2-chamber view (TEE)
      iv. TG LAX view (TEE)

2. **Measurement of LV internal dimensions in diastole (LVIDd) and systole (LVIDs) measured at the level of the mitral chordae level.**
   a. Imaging planes
      i. TG LAX view (TEE)
      ii. TG 2-chamber (TEE)
   b. Issues
      i. Avoids foreshortening in the ME 4-chamber and ME LAX view
ii. Avoid ME views due to loss of lateral endocardial surface

3. Endocardial Fractional Shortening (%FS)
   a. Ventricular diameters from M-Mode measurements
      i. \( \% \text{FS} = \left( \frac{LVEDD - LVESD}{LVEDD} \right) \times 100 \)

4. Midwall Fractional shortening (%MWFS)
   1. Superior to fractional shortening
   2. Contraction of LV midwall muscle fibers as opposed to fibers at endocardium
   3. Useful in underlying systolic dysfunction with concentric hypertrophy
   4. Difficult to calculate
   5. Calculate inner shell value

   Midwall Fractional Shortening
   Inner shell = \([LVID_{d} + SWT_{d}/2 + PWT_{d}/2]^{3} - LVID_{d}^{3} + LVID_{s}^{3}\)^{1/3} - LVID_{s}

   MWFS = \([(LVID_{d} + SWT_{d}/2 + PWT_{d}/2) - (LVID_{s} + \text{inner shell})]\) x 100

5. Volumetric measurements
   a. Imaging planes
      i. TG MidPAP SAX (TEE)
      ii. ME 4-chamber (TEE)
      iii. ME 2-chamber (TEE)
      iv. Midpapillary SAX (TTE)
      v. Apical 4-chamber (TTE)
      vi. Apical 2-chamber (TTE)
   b. Issues
      i. Manual tracing of endocardial border
      ii. Exclusion of the papillary muscles in the tracing (DO NOT TRACE AROUND THE PAPILLARY MUSCLES)
      iii. Basal border of LV cavity delineated by line connecting the MV insertions at lateral and septal borders
      iv. The longer of the two LV lengths (apical 4 vs. apical 2) should be utilized for the calculation
      v. End-diastole
         1. defined by the first frame after mitral closure
         2. defined by the frame in the cardiac cycle when cardiac dimension the largest
      vi. End-systole
         1. Defined by the first frame after aortic valve closure
         2. Defined by the frame in the cardiac cycle when cardiac dimension the smallest

6. Volume Measure-Utilization of 2D or 3D echocardiography. Volume calculations from linear dimensions that rely on a fixed geometric shape such as a prolate ellipse are no longer recommended due to varying LV geometric shapes. Therefore Teichholz and Quinones methods for calculating LV volumes are no longer recommended.
a. Biplane method of disks (modified Simpson’s rule)
   i. Summation of stacked elliptical disks
   ii. Height of each disk is calculated as a fraction (1/20) of the LV long axis based upon the longer of the two lengths from the 2- and 4-chamber views.
   iii. Cross-sectional area of disk based on the two diameters obtained from the 2- and 4-chamber views

b. Area-length method
   i. LV assumed to be bullet-shaped
      1. Mid LV cross-sectional area is computed by planimetry in the parasternal short axis view and the length of the LV is taken from the midpoint of the annulus to the apex in the apical 4-chamber.
      2. Measurements repeated at end diastole and end systole.
      3. Formula Volume = \( \left[ \frac{5 \text{ (area)} \text{ (length)}}{6} \right] \)

7. Ejection Fraction
   a. Ejection fraction (%) = \( \frac{\text{EDV-ESV}}{\text{EDV}} \times 100 \)
   b. May use either volumes obtained by Biplane method of disc or Area-length method
   c. With good alignment, TEE and TTE values show good correlation
   d. LV EF somewhat higher in healthy women than men
   e. LV EFs < 52% for males, and < 54% for women are suggestive of abnormal LV systolic function
   f. 3D values for volumes differ from 2D as they do not depend upon geometric assumptions and not prone to image plane positioning errors.
   g. Comparison of 3D volumes to MRI (gold standard) have confirmed 3D to be accurate and better agreement, lower scatter and lower intraobserver and interobserver variability than 2D echocardiography.

8. Fractional Area Change (%FAC)
   a. \( \%\text{FAC} = \left[ \frac{(LVEDA-LVESA)}{LVEDA} \right] \times 100 \)

9. Stroke Volume (SV) and Cardiac Output (CO)
   a. \( \text{SV} = \text{Area} \times \text{VTI} \)
      i. Can be utilized for RV (RVOT) or LV (LVOT)
      ii. Basis for Qp/Qs
      iii. \( \text{Area} = \left( \frac{D}{2} \right)^2 \times \pi \)
      iv. \( \text{VTI} = \) calculated by tracing outline of velocity spectral display
   b. \( \text{CO} = \text{SV} \times \text{HR} \)

10. Systolic Index of Contractility (dP/dt)
    a. Rate of Ventricular Pressure Rise
    b. While load dependent, dP/dt is the most load insensitive of the “Load-dependent” indices with no affect to changes in
afterload or wall motion abnormalities and only mildly affected by preload changes

c. Initial acceleration of the mitral regurgitation jet represents contractile force generated during the IVCT (time it takes to go from 1 m/s to 3 m/s.
   i. dP/dt requires that a measurable MR jet is present
   ii. dP/dt > 1200 mmHg/s (dt<26 ms) is normal
   iii. dP/dt < 800 mmHg/s (dt>40 ms) is depressed systolic function

11. Myocardial Performance Index (MPI or TEI Index)
   a. Ratio of total LV isovolemic time to ejection time
   b. MPI=(IVRT +IVCT)/Systolic Ejection Period
   c. MPI = 0.4 normal, MPI > 0.6 implies either systolic or diastolic dysfunction

Load Independent Measures are not related to preload or afterload.

12. Left Ventricular Mass, Geometry and Relative Wall Thickness
   a. Important risk factor for and strong predictor of cardiovascular events and offers prognostic information independent of age, gender and other predictors.
   b. Can be measured by M-mode, 2D or 3D methods.
   c. LV modeled as a prolate ellipse of revolution for M-mode and 2D method of calculation
   d. Based upon the subtraction of the LV cavity volume from the volume enclosed by the LV epicardium to obtain LV muscle or shell volume. This LV muscle volume is then multiplied by the myocardial density
   e. LV mass = 1.05 x (Total LV volume-LV Chamber volume)
   f. Linear Method-Cube Formula (M-mode)
      LV mass = 0.8 x \{1.04[(LVIDd+PWTd+SWTd)3-(LVIDd)3]\} +0.6 g
      i. Normally indexed to BSA and gender for linear method (M-mode).
         1. Women=43-95 g/m²
         2. Men=49-115 g/m²
   g. Cubing of primary measurement can introduce magnify error.
   h. 2D based formula incorporates a truncated ellipsoid or Area-length calculation
      i. Normally indexed to BSA and gender for 2D method.
         1. Women=44-88 g/m²
         2. Men=50-102 g/m²
   j. 3D method measures volume directly and avoids geometric assumptions and incorporates complex ventricular shapes and the utilization of this technology is emerging. Normal limits of 3D echocardiographic LV mass data are still being defined.
Myocardial area \( (A_m) = \) Total LV area \( (A_1) \) – LV cavity area \( (A_2) \)

13. Regional Wall Thickness (RWT) = \( 2 \times \) inferolateral wall thickness in diastole/LVID

   i. Concentric—RWT ≥ 0.42
   ii. Eccentric—RWT ≤ 0.42

Estimation of LV mass based upon area-length of truncated ellipse from the short axis and four-chamber views. \( A_1 = \) total LV area, \( A_2 = \) LV cavity area, \( A_m = \) myocardial area. Mathematic formulation (A-L or TE) then used to stack these areas and calculate overall \( A_m \) or shell volume. Modified from Lang et al.
14. Tissue Doppler Imaging (TDI)
   a. Doppler imaging of movement of cardiac structures
      i. TDI velocity is commonly sampled from the septal mitral annulus to assess the descent of the mitral annulus toward the apex (velocity > 5.4 cm/sec correlates with EF > 50%).
      ii. Requires software package, angle dependent and not utilized in all patients.

15. Speckle Tracking
   a. Angle independent
   b. Myocardial shortening and strain can be calculated by measuring the changing distance between speckles during systole and diastole.

16. Global Longitudinal Strain (GLS)
   a. Lagrangian strain is defined as the change in length of object within a certain direction relative to its baseline length.
   b. Strain (%) = (Lt-Lo)/Lo x 100 where Lt is length at time t, and Lo is the initial length at time 0.
   c. GLS (%) = (MLs-MLd)/MLs x 100 where ML is myocardial length at end-systole (MLs) and end-diastole (MLd)
d. Negative number are generated as ML<sub>L</sub> and therefore it is recommend all strain values be associated with mention of an increase or decrease in the absolute value of strain.

e. Endocardial vs. midwall vs. average deformation. Still undecided although most literature focused upon midwall.

f. Unable to define a current universal normal value based upon differences in vendors and software packages although a peak GLS in the range of -20% can be expected in a healthy individual.

g. Women have slightly higher absolute values for GLS than males and strain values decrease with age.

Reference values for common quantitative assessment of left ventricular size, volumes and function are extensively published in consensus statements and not reproduced in this document. Most reference values are based upon TTE examinations in healthy individuals and may not directly correlate with TEE values. The reader is referred to one of the many society consensus statements, which have published reference values. Recently, “normal values” have been published for 3D TTE in healthy patients and are reproduced below for reference. With further studies, refinements to standard normal values based upon 3D TTE and TEE will be incorporated into consensus statements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D LVEDV (ml/m²)</td>
<td>85</td>
<td>72</td>
</tr>
<tr>
<td>3D LVESV (ml/m²)</td>
<td>34</td>
<td>28</td>
</tr>
<tr>
<td>Ejection fraction (%)</td>
<td>54</td>
<td>57</td>
</tr>
<tr>
<td>SV index (ml/m²)</td>
<td>25</td>
<td>24</td>
</tr>
<tr>
<td>LV mass (g/m²)</td>
<td>97</td>
<td>90</td>
</tr>
<tr>
<td>Sphericity index</td>
<td>0.49</td>
<td>0.48</td>
</tr>
</tbody>
</table>

(modified from Muraru, et al.)

**Echocardiographic Assessment of Regional LV Function**

TEE is highly sensitive to evaluate regional function and underlying pathologic conditions such as myocardial ischemia, infarction or cardiomyopathies. Assessment of regional (segmental) function depends upon observed changes in inward radial motion and systolic wall thickening. The LV is divided into 16 or 17 segments according to ASE and SCA guidelines. The basal and mid levels of the ventricle are divided into six segments and the apex is divided into four segments. In 2002, the 16-segment model was expanded to 17-segments and now includes the apical cap. This change was adopted to mirror other cardiac imaging techniques and reporting structure. For wall-motion analysis, the 16-segment model is sufficient, as the apical cap is not considered a segment for myocardial contraction analysis.

**Regional Anatomy**

<table>
<thead>
<tr>
<th>Level</th>
<th>Segment(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal (6)</td>
<td>Anterior</td>
</tr>
<tr>
<td></td>
<td>Anteroseptum</td>
</tr>
</tbody>
</table>
After identification of the 16 contractile segments, regional function can be assessed by the following degree of inward radial motion and the degree of systolic wall thickening. Regional function can be classified as indicated in the table below and can individual segments can be graded, as well as an overall wall motion score index reflecting overall global function can be calculated for the left ventricle.

<table>
<thead>
<tr>
<th>Regional Function</th>
<th>Grade</th>
<th>Inward Radial Motion</th>
<th>Systolic Wall Thickening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal or hyperkinesis</td>
<td>1</td>
<td>&gt; 30%</td>
<td>Marked</td>
</tr>
<tr>
<td>Hypokinesis</td>
<td>2</td>
<td>10% to 29%</td>
<td>Reduced</td>
</tr>
<tr>
<td>Akinesis</td>
<td>3</td>
<td>&lt;10%</td>
<td>Negligible</td>
</tr>
<tr>
<td>Dyskinesis</td>
<td>4</td>
<td>0 (systolic thinning or stretching)</td>
<td>Systolic Thinning (e.g. aneurysms)</td>
</tr>
</tbody>
</table>

Wall motion score index = (sum of all wall scores)/(number of segments visualized)

The current 2015 Guidelines have eliminated the regional function distinction for aneurysms with a grade 5 from the wall motion scoring system and all segments should be graded from 1-4.

**Coronary Artery Distribution**

Individual segments can be associated with one or more coronary artery distribution territories. Of the three coronary arteries, only the left anterior descending (LAD) and the right coronary artery (RCA) have isolated myocardial segments. The left circumflex artery (CX) does not perfuse one exclusive segment of the left ventricle and these segments maybe perfused by a one of two coronary arteries based upon coronary anatomy. There is variability in the literature regarding coronary artery distribution models reflecting older models of coronary perfusion. The distribution model listed below reflects the ASE/EAE Consensus statement published by Lang, et al in 2015. The seventeen-segment model should be utilized when discussing myocardial perfusion models.
<table>
<thead>
<tr>
<th>Level</th>
<th>Segment(s)</th>
<th>Coronary Artery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal (6)</td>
<td>Anterior</td>
<td>LAD</td>
</tr>
<tr>
<td></td>
<td>Anteroseptum</td>
<td>LAD</td>
</tr>
<tr>
<td></td>
<td>Inferoseptum</td>
<td>RCA</td>
</tr>
<tr>
<td></td>
<td>Inferior</td>
<td>RCA</td>
</tr>
<tr>
<td></td>
<td>Inferolateral</td>
<td>RCA or CX</td>
</tr>
<tr>
<td></td>
<td>Anterolateral</td>
<td>LAD or CX</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MidPapillary (6)</td>
<td>Anterior</td>
<td>LAD</td>
</tr>
<tr>
<td></td>
<td>Anteroseptum</td>
<td>LAD</td>
</tr>
<tr>
<td></td>
<td>Inferoseptum</td>
<td>RCA or LAD</td>
</tr>
<tr>
<td></td>
<td>Inferior</td>
<td>RCA</td>
</tr>
<tr>
<td></td>
<td>Inferolateral</td>
<td>RCA or CX</td>
</tr>
<tr>
<td></td>
<td>Anterolateral</td>
<td>LAD or CX</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apex (4 or 5)</td>
<td>Anterior</td>
<td>LAD</td>
</tr>
<tr>
<td></td>
<td>Septal</td>
<td>LAD</td>
</tr>
<tr>
<td></td>
<td>Inferior</td>
<td>LAD</td>
</tr>
<tr>
<td></td>
<td>Lateral</td>
<td>LAD</td>
</tr>
<tr>
<td></td>
<td>Apical cap</td>
<td>LAD or CX</td>
</tr>
</tbody>
</table>

A common view to assess LV function and segmental function is the TG MidPap SAX as 6 segments of myocardium are visualized and typically all three coronary arteries perfuse ventricular segments at this left ventricular level. All 6 views (4-chamber, 2-chamber, ME LAX and the three levels of the TG SAX) should be evaluated to identify all 17 segments and the associated coronary perfusion.
LV Function and 3D TEE

3D imaging is beginning to be common in clinical practice and both single-beat and real-time 3D acquisition is being utilized for evaluation of LV volume and function. “Full-volume” data sets can be obtained of the left ventricle and off line analysis with delineation of endocardial borders can be performed. Advantages of 3D imaging and measurements over 2D techniques include avoidance of geometric assumptions. Complete systolic and diastolic volumes can be obtained and then calculation of volume-based functions including stoke volume and ejection fraction can be determined. Global left ventricular volumes, EF measurements and function using real-time 3D TEE is quick, more accurate and reproducible than with 2D echocardiography and correlate highly with cardiac MRI. 3D derived volumes are underestimated when compared to MRI derived values. This underestimation may be related to the presence of LV cavity trabeculations, which are not consistently identified, by 3D echocardiography and one beat analysis.
Interobserver variability in volume determination is less with 3D echocardiography in comparison to 2D and normal reference values have not been defined for 3D derived volumes. 3D echocardiography has been demonstrated to be useful in the assessment of regional left ventricular wall motion and quantification of systolic dyssynchrony. With 3D echocardiography, individual LF segmental volumes are plotted versus time in the cardiac cycle. The plots evaluate temporal differences in segmental time to minimum volume (maximal contraction). In ventricles with a normal systolic dyssynchrony index, regional minimal volume occurs at the same time in ventricular systole for all segments. In a left ventricle with dyssynchrony, there is dispersion in the timing when regional segments attain their minimum volume. A systolic dyssynchrony index (SDI) may be calculated which is the standard deviation of regional ejection times. A recent study by Meris, et al, investigating intraoperative 3D TEE and its role in quantification of LV global function, demonstrated that image acquisition time, and reproducibility was not statistically different than conventional 2D imaging. 3D TEE quantification though was associated with larger volumes and longer analysis times but these larger volumes did not affect the overall LV function classification models. Based upon the closer limits of agreement with MRI and better reproducibility the 2D echocardiography, 3D echocardiography can be recommended for standard utilization to determine LV volumes and ejection fraction. In the future, systolic dyssynchrony index, 3D strain measurements and LV shape analysis present opportunities to redefine diagnosis and management strategies. As stated by the EAE/ASE consensus statement regarding 3D echocardiography, “3D TTE and TEE assessment of LV volumes and ejection fraction is recommended over the use of 2D echocardiography.” 3D echocardiography is redefining the science and understanding of cardiovascular imaging and many redefinitions of current beliefs and new findings will be elucidated by this new technology.

Further Reading:

5. Lang RM, Bierig M, Devereux RB, et al. Recommendations for chamber quantification: A report from the American Society of Echocardiography’s Guidelines and Standards Committee and the Chamber Quantification Writing Group, developed in conjunction with the European Association of Echocardiography, a branch of the European Society of Cardiology. J Am Soc Echocardiogr 2005;17:1086-1119.
6. Lang RM, Badano LP, Mor-Avi V, et al. Recommendations for cardiac chamber quantification by echocardiography in adults: An update from the


