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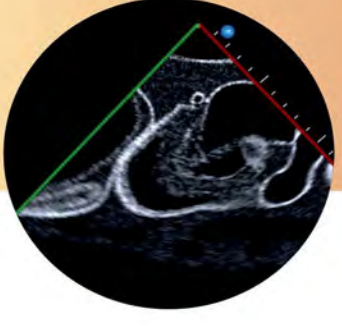
CLINICAL SIMULATION IN MEDICINE

For all Examinations in Cardiology, Critical Care, Anesthesia and Pulmonary Medicine











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Chapter 4

Understanding Echocardiographic Assessment of Left Ventricular Systolic and Diastolic Function for Simulation Training

Navin C Nanda, Munveer Thind, Saurabh Gaba, Marisa Joson, Serkan Bulur, Kamal Ahuja, Naga Sai Shravan Turaga, Sameer Srivastava

Chapter Outline

- Diastolic Function Assessment
- Conventional Two-dimensional Echocardiography
- Conventional and Color Doppler Echocardiography
- Tissue Doppler Imaging
- Two-dimensional Speckle Tracking Echocardiography and Velocity Vector Imaging
- Three-dimensional Speckle Tracking Echocardiography

DIASTOLIC FUNCTION ASSESSMENT

When a patient presents with dyspnea in spite of a documented normal systolic function, it is essential to consider diastolic dysfunction (DD) as a cause of heart failure. Diastolic heart failure (DHF) is also known as heart failure with preserved or normal left ventricular ejection fraction (LVEF). In this condition, left atrial pressures, which are equivalent to left ventricular filling pressures in the absence of mitral stenosis, are elevated causing increased pulmonary venous pressures and eventually affect the pulmonary circulation leading to dyspnea and pulmonary hypertension. Left ventricular diastolic function can be evaluated by two-dimensional transthoracic echocardiography (2DE), Doppler studies such as transmitral inflow velocities, pulmonary venous flow and flow propagation velocity, tissue Doppler imaging, pulmonary artery pressure, and with the emerging techniques of velocity vector imaging and 2D and three (3)D speckle tracking echocardiography.

CONVENTIONAL TWO-DIMENSIONAL ECHOCARDIOGRAPHY

According to current guidelines, DHF is diagnosed in the presence of the following three criteria: clinical picture consistent with heart failure, demonstration of preserved LVEF and documentation of diastolic dysfunction (DD).[1] Conventional two-dimensional echocardiography (2DE) can accurately measure LVEF and determine whether systolic dysfunction is present. Left atrial (LA) size, which is best assessed using LA volume, reflects mean pulmonary wedge pressure and is a reliable marker of chronic DD. If LA size is normal, elevated LA pressures are less likely to be present

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except in an acute setting where the LA may not have had time to dilate.[2] Alternatively, a dilated LA may not always be due to DD because conditions like atrial fibrillation, flutter, bradycardia, mitral valve disease, hypertension and anemia may cause significant atrial dilatation.[3] Concentric LV hypertrophy characterized by increased LV mass and relative wall thickness and remodeling, wherein LV mass is normal but relative wall thickness is increased, can be noted in DD.[4] Likewise, accurate determination of wall motion abnormalities is important as they contribute to decreased relaxation and compliance. DHF is associated with LVEF > 50% and LV mass ≥ 90 g/m^2 for women and ≥115 g/m^2 for men, LA volume index ≥34 mL/m^2 and abnormal wall motion.[1,2]

CONVENTIONAL AND COLOR DOPPLER ECHOCARDIOGRAPHY

Transmitral Velocities

Echocardiographic evaluation of diastolic function has been conventionally carried out by measuring the transmitral flow parameters. The mitral inflow Doppler profile provides the following indices for assessing diastolic function:

1. **E wave (early diastolic filling velocity).**
2. **A wave (late diastolic filling velocity due to atrial contraction).**
3. **E/A** (E to A ratio).
4. **DT** (deceleration time which is the time interval from the peak of E to its extrapolation to the baseline, and
5. **IVRT** (isovolumic relaxation time which is the time interval from aortic valve closure to mitral valve opening).

   DD may be present when any of the following is noted: (a) E/A < 1 or >2; (b) DT <150 ms or >220 ms or (c) **IVRT** <60 ms or >100 ms.[4]

The **peak E velocity** may be augmented by either increased LA pressure in the presence of heart disease, or by rapid LV relaxation typical of normal young adults. Hence, a high E/A may either be normal or abnormal. The transmitral flow parameters should be interpreted in the context of the loading conditions of the heart. Preload reduction decreases LA pressure and reduces the gradient between the LA and LV, leading to decreased E velocity and increased DT as it takes a longer time for the LV to fill. An increase in preload, as in severe mitral regurgitation, on the other hand, increases E velocity and reduces DT as there is increased gradient between the LA and LV pushing blood forward. In tachycardia or nonsinus rhythm, it may not be possible to acquire the biphasic E and A waves in the transmitral flow signal and evaluation of E, A and DT would be difficult.

Diastolic dysfunction can be graded according to variations in E/A ratio. In a normal heart, the LA empties rapidly into a relaxed and compliant LV resulting into a tall E wave and a shorter A wave, E > A. In Grade I DD or impaired relaxation with normal filling pressures, E < A since atrial contraction is the main contributor to LV filling. In Grade II or pseudonormalization pattern characterized by impaired relaxation and mildly elevated LV filling pressures, E > A. Finally, in Grade III or restrictive pattern with markedly elevated filling pressures and decreased deceleration time, a high E/A ratio is noted **(Figures 1 and 2)**.

The Valsalva maneuver, which by increasing intrathoracic pressure reduces cardiac preload, can be used to differentiate the normal pattern from pseudonormalization as they both present as E > A. In the presence of DD, the decreased preload with Valsalva

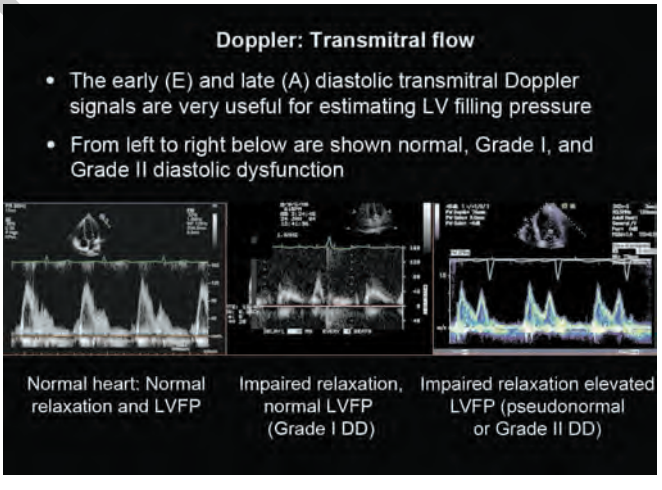


Figure 1 Transmitral diastolic inflow for the assessment of left ventricular filling pressures. (Left panel): mitral inflow in the normal heart shows early transmitral diastolic inflow greater than late transmitral diastolic inflow (E > A) due to rapid diastolic function and normal left ventricular filling pressures (LVFP); (Middle panel): in the patient with impaired LV relaxation but normal LVFP, E is lower than A, as the LV depends more on atrial kick for LV filling; this is also termed Grade I diastolic dysfunction (DD); (Right panel): in the patient with pseudonormal filling pattern, there is impaired LV relaxation but E > A, and is caused by elevated LA pressures; this is also termed Grade I diastolic dysfunction (DD). Valsalva maneuver and tissue Doppler imaging can help distinguish normal from pseudonormal filling.

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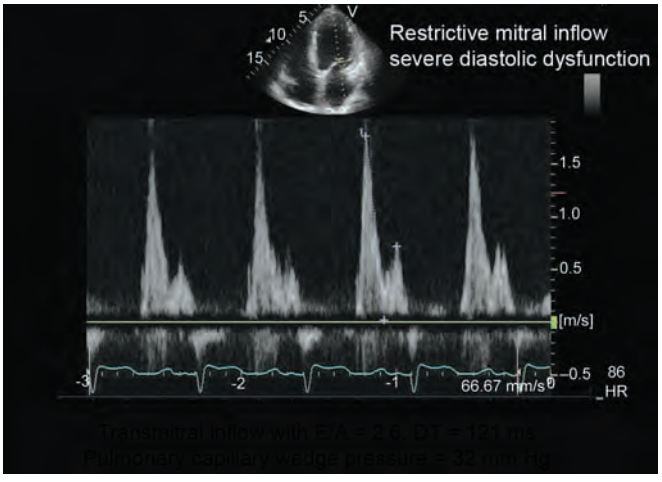


Figure 2 Restrictive transmitral filling pattern. When left ventricular (LV) filling pressures are severely elevated due to increased LV diastolic stiffness, early transmitral diastolic flow (E) has a high velocity because there is an initial high gradient between very elevated left atrial (LA) pressure and LV diastolic pressure. However, due to elevated resting LV diastolic pressures, the LA and LV pressures rapidly equilibrate, resulting in a rapid deceleration time (DT) of transmitral E. In general, in a patient with cardiac disease, restrictive filling occurs when E/A > 2 and DT < 150 milliseconds. A = late transmitral diastolic velocity.

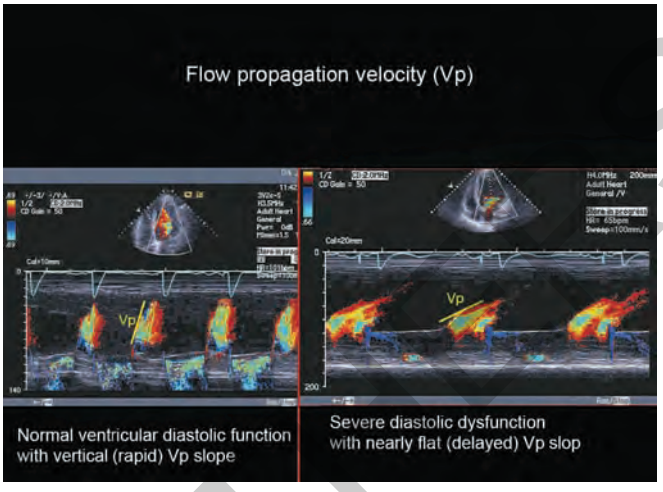


Figure 3 Color Doppler flow propagation velocity (Vp) in the assessment of left ventricular diastolic function. Placing the color Doppler sample volume from the mitral annular level to the left ventricular (LV) apex, the more rapid the LV relaxation, the faster blood travels from the mitral annular level to the LV apex, and hence the more vertical the color Doppler mitral inflow M-mode and the more rapid the Vp slope (left panel). On the other hand, the more impaired the LV relaxation, the slower it takes for blood to go from the mitral annular to the LV apex, hence a "flatter" Vp slope (right panel).

will unmask the tall E and elicit the pattern E < A. When diastolic function is normal, E > A will remain. Likewise, Valsalva maneuver can help determine whether a restrictive pattern is reversible or not. With reversibility, usually referred to as Grade IIIA DD, the pattern can change to either E < A or E > A. With irreversible restrictive pattern or Grade IIIB, the E/A ratio remain the same. [5]

In reality, Valsalva maneuver is not always a practical tool to use. Not all patients can follow the instructions and the procedure is not standardized. The innovation brought about by tissue Doppler imaging (TDI) has lessened the performance of this maneuver particularly in busy echocardiography laboratories.[4]

Flow Propagation Velocity

This modality combines color Doppler imaging and M mode using apical 4-chamber view to measure blood transit time from the mitral valve annulus to the LV apex. The early diastolic filling wave by color M mode, which appears in red color as blood flows from the mitral valve to the LV apex is identified (V_p). The slope of this early diastolic M mode is rapid and vertical with normal diastolic function. With DHF, the slope gets flatter and flatter reflecting progressively impaired relaxation. **Also, E/V_p correlates with mean LA pressure such that E/V_p >15 reasonably correlates with PCWP >15 mm Hg.**[6,7] In practice, many echo laboratories do not use this modality as many technological concerns contribute to significant inter observer variability **(Figure 3)**.[7, 8]

Pulmonary Venous Flow

Pulsed wave Doppler of the pulmonary veins is also used to evaluate for DD. In a normal heart, blood flows rapidly through the pulmonary veins into the LA and passes through the mitral valve into the LV. The Doppler signals are made up of forward systolic (S), and diastolic (D) velocities into the LA and a backward late diastolic A reversal wave (Ar) corresponding to atrial contraction. Other measurements include the duration of Ar velocity and the time difference between Ar duration and mitral A wave duration (Ar-A), systolic filling fraction and DT (deceleration time). In normal subjects, S < D (due to rapid diastolic suction in the healthy LV) and Ar < 35 ms. In grade I DD, S > D as rapid diastolic function is lost. In the setting of elevated LA pressure S < D, and in significiantly elevated LA pressure DT of D wave < 150 ms. Therefore, as with mitral inflow E/A, pulmonary

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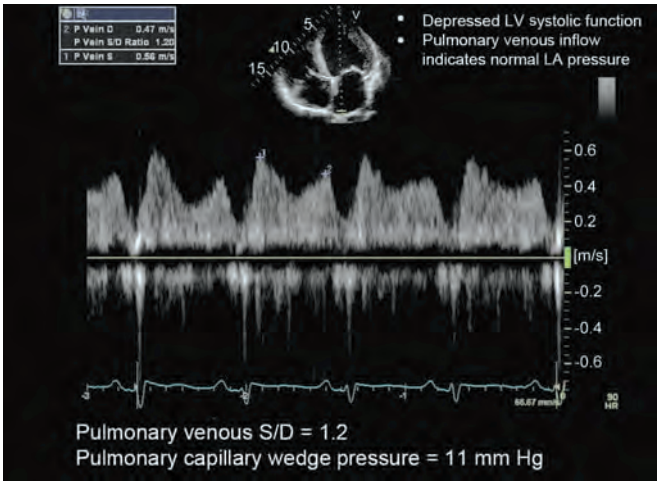


Figure 4 Pulmonary venous Doppler velocities in the assessment of left atrial pressures. In normal heart, systolic pulmonary venous (PV) flow (S) is lower than diastolic PV flow (D), as rapid left ventricular (LV) suction during diastole results in elevated PV D velocities; thus, PV S < D. In patients with impaired LV relaxation and elevated LA pressure, when the mitral valve (MV) is closed in ventricular systole, the elevated LA pressure prevents PV S flow, and therefore most flow occurs when the MV opens, resulting in S < D. Therefore, as with mitral inflow velocities, PV velocities are also prone to pseudonormal filling. In this example, there is impaired LV relaxation due to cardiomyopathy, but LA pressure is not elevated; thus, when the MV is closed (LV systole), there is unimpeded flow through the PV, and hence S > D.

venous S/D also has normal and pseudonormal patterns. Ar-A velocity duration >30 ms indicates an elevated LV end diastolic pressure. DD can also be graded using the values of the pulmonary venous flow velocities mentioned above.[9]

It is obvious that measurement of pulmonary venous flow is not always feasible, as high quality recordings suitable for measurement are not always obtainable. In contrast to mitral inflow velocities, only a small number of studies have documented the prognostic role of pulmonary venous flow **(Figure 4)**.[10-12]

Pulmonary Artery Pressure (PAP)

When there is elevated LA pressure, this pressure is transmitted back into the pulmonary veins and across the pulmonary venous-capillary bed into the pulmonary arterioles then into the pulmonary arteries leading to pulmonary arterial hypertension (PAH). In this way, PA pressure estimated by addition of right atrial (RA) pressure (by assessing inferior vena cava size and response to respiration) is a good surrogate marker of significant, and often chronic, LA pressure elevation. It has been proven that PA systolic pressure (PASP) >35 mm Hg often characterizes advanced or significant LV DD with elevated LA pressures.[4,13] However, as with LA volume, the existence of significant PAH does not necessarily mean significant DD, as significant elevation in pulmonary vascular resistance (PVR) due to intrinsic lung disease must first be excluded. Likewise, normal PASP can be helpful in ruling out significant and long-standing LA pressure elevation, as long as a complete tricuspid regurgitation (TR) jet is obtained with correct Doppler sample volume angulation in respect of the direction of TR, and with correct RA pressure estimation. PA end-diastolic pressure, which in the absence of significant elevations in PVR can be a good estimate of mean LA pressure, can be approximated from the pulmonary artery regurgitation diastolic wave, with RA pressure then added to it as is done with PASP.[13]

TISSUE DOPPLER IMAGING

Measurement of mitral annulus velocities using TDI has been shown to be a sensitive tool to evaluate for DD since it is less dependent on cardiac loading conditions. Contraction and relaxation of myocardial segments result in long axis shift of the mitral annulus toward the quite immobile LV apex during systole and in the opposite direction in diastole. Three velocities are recorded:

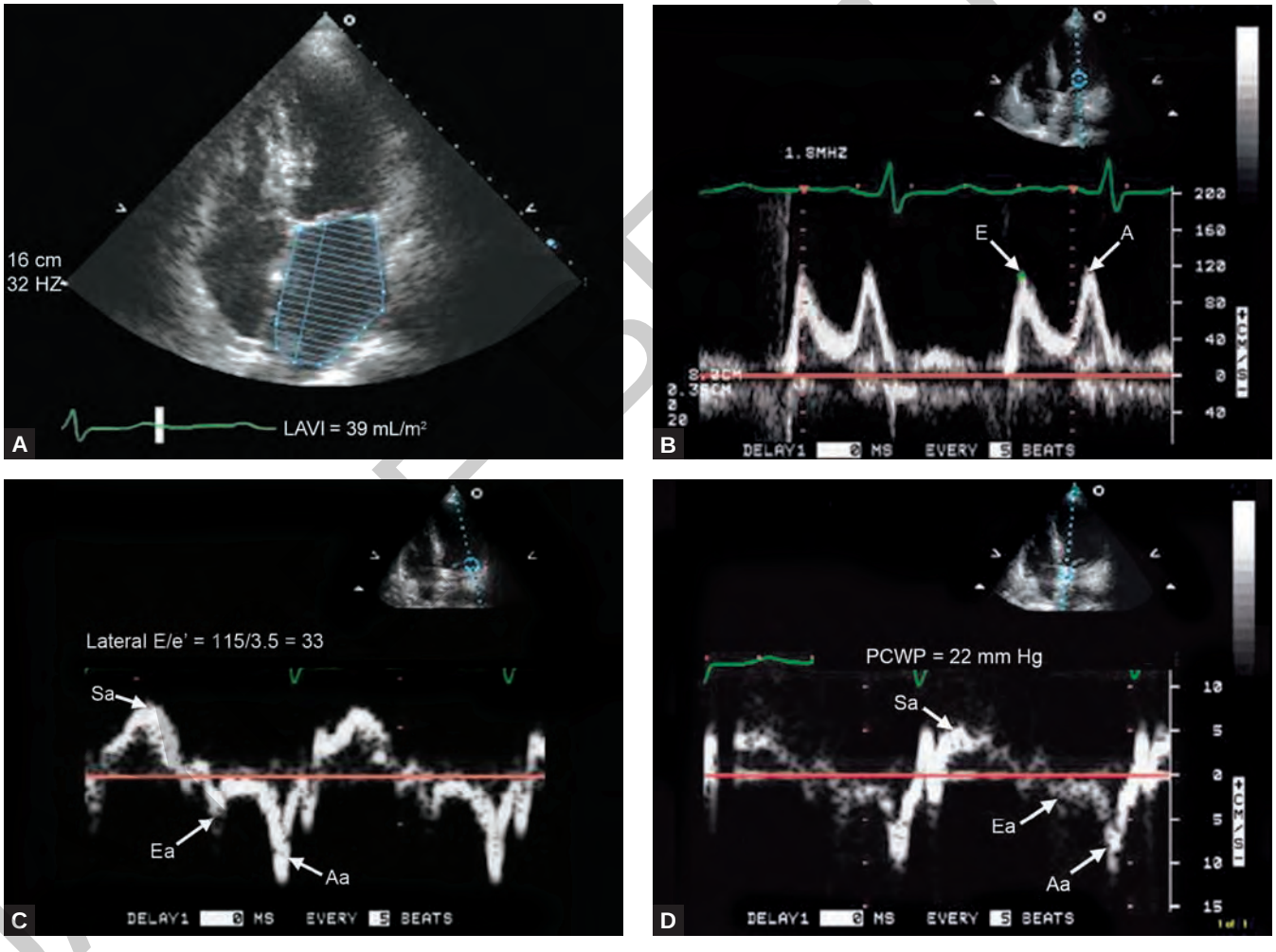
a. **S′ corresponding to ventricular ejection,**
b. **E′ corresponding to early filling as in the E of transmitral Doppler.**
c. **A′ corresponding to late filling as in A wave.**[8,13,14]

Of the three velocities recorded, E′ is considered to be the most valuable for the evaluation of DD. E′ progressively decreases as relaxation becomes slower in the setting of many cardiac diseases such as dilated, restrictive and hypertrophic cardiomyopathies.[8] It is less affected by preload and remains low in patients with pseudonormalized E/A. These velocities are recorded at the septal and lateral annuli. Septal E′ is usually less than lateral E′, except in the setting of lateral wall infarction or constrictive physiology. Studies suggest that the lateral E′ is preferable if one is obtaining only a single measurement in a patient with normal LVEF, as the septal E′ has been shown to be changed by preload in patients with normal LV function, although this alteration may decrease as LV relaxation becomes more deranged. Also, the septal E′ may be affected by right ventricular DD.[15] Computing for E/E′ provides an

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estimate of LV filling pressure, with E/lateral E′ >12 and E/septal E′ > 15 indicating increased LV filling pressure. With regional LV dysfunction, it is advised to utilize the average value of E′ of septal and lateral annuli to better reflect LV filling pressures.[16] Tissue Doppler imaging also measures the time interval, TE-E′ which is the time interval between the QRS complex and the onset of mitral E velocity minus the time interval between the QRS and the onset of E′. In particular, IVRT/T E-E′ < 2 reasonably identifies patients with elevated LV filling pressures.[17] Diastolic dysfunction can also be graded in the same way as with transmitral Doppler velocities using the values for E′ and E/E′.[6]

Tissue Doppler imaging has the edge, against other modalities of being easy to execute and validate in clinical practice.[18] There are procedural limitations, however, such as its being angle dependent and requiring proper attention to the location of the Doppler sample volume which should be placed at the tips of the mitral leaflets for measurement of E and A. The presence of significant mitral annular calcification, surgical rings, mitral stenosis, significant mitral regurgitation, prosthetic mitral valve and constrictive pericarditis, among others affect the mitral inflow velocities rendering the application of E to E′ ratio unreliable in these settings **(Figures 5A to D)**.[19]



Figures 5A to D Tissue Doppler imaging for the assessment of left ventricular (LV) diastolic function. (A) An apical four-chamber view with moderate to severe dilation of the left atrium (LA) with an LA volume index of 39 mL/m^2; (B) Elevated early transmitral diastolic velocity (E) = 117 cm/s; (C) Very depressed mitral lateral annular early diastolic relaxation velocity (e') = 3.5 cm/s; (D) Very depressed septal tissue Doppler (TD) early diastolic velocity (e') = 2.5 cm/s. Therefore, E/e' septal = 47, and E/e' lateral = 33, indicating severely impaired LV relaxation with elevated LV filling pressures.

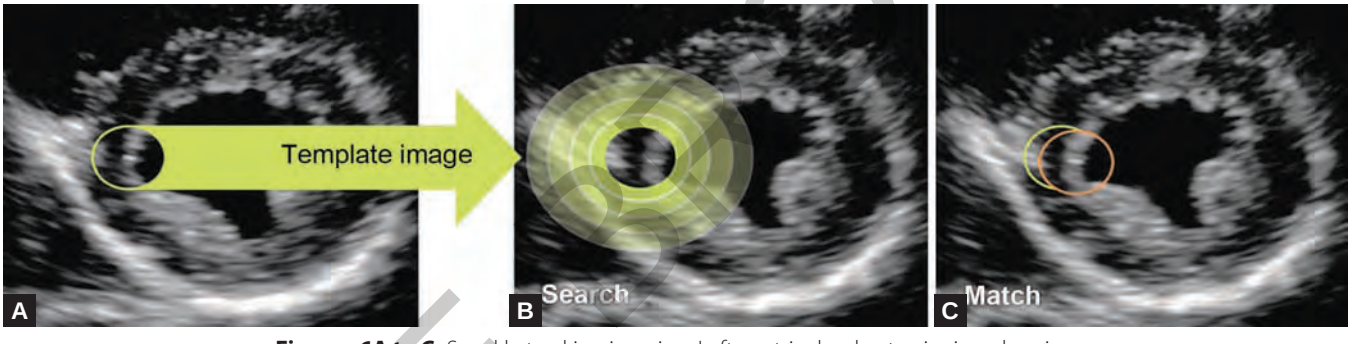
Abbreviations: LAVI, left atrial volume index; PCWP, Pulmonary capillary wedge pressure.

TWO-DIMENSIONAL SPECKLE TRACKING ECHOCARDIOGRAPHY AND VELOCITY VECTOR IMAGING

Two-dimensional speckle tracking echocardiography (2D STE) is an innovative technology of cardiac imaging that allows for calculating complex cardiac movement based on frame-to-frame tracking of ultrasonic speckles on gray scale 2D images. Speckles are small dots or groups of myocardial pixels that are routinely created by the interface of ultrasonic beams and the myocardium. Identifying and tracking these speckles all through the cardiac cycle by 2D technology provides information about myocardial muscle mechanics which can then be used to evaluate cardiac function and confirm the presence of abnormalities. Many vendors have developed algorithms for speckle tracking **(Figures 6A to C)**.[20-22]

Though TDI also provides information on myocardial velocities from which myocardial deformation (strain) can be obtained, the method is complex and requires parallel alignment of the ultrasound beam to tissue movement. On the other hand, 2D STE is angle independent since it is based on 2 DE and not on Doppler. **Table 1** compares 2D STE with TDI and presents the advantages and disadvantages of each technology.

Clinically, 2D STE has been utilized to evaluate systolic and diastolic function and a host of cardiac pathologies like ischemia, cardiomyopathy, valvular and congenital heart diseases, and the athlete's heart, among others. It is also being utilized to evaluate the effectiveness of treatment as in cardiac resynchronization therapy and the effects of chemotherapeutic drugs and stem cell therapy on the heart.[22]



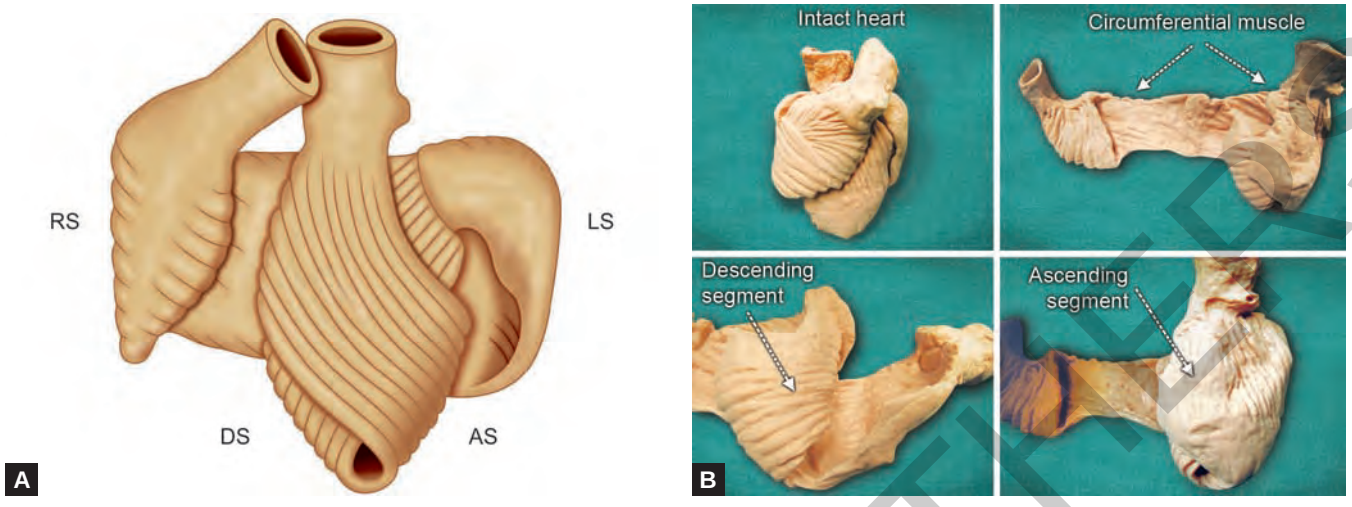
Figures 6A to C Speckle tracking imaging. Left ventricular short-axis view showing frame-by-frame tracking of a large group of pixels (denoted by a circle). *Courtesy:* Toshiba Medical Systems Europe BV.

TABLE 1 Comparison of tissue Doppler imaging with speckle tracking for evaluation of strain

Tissue Doppler imaging	*Speckle tracking*
Dependent on angle of insonation	Angle independent
Can measure deformation only along one axis (axis of the transducer)	Can measure longitudinal, radial, and circumferential strain. Can also measure left ventricular twist mechanics
Movement assessed in relation to transducer	Movements assessed in relation to adjacent speckles
Higher frame rates and hence good temporal resolution	Lower frame rates and poor temporal resolution. Hence limited utility in tachycardic patients and in those with nonsinus rhythms
Limited spatial resolution	Better spatial resolution
Measures regional strain only	Both regional and global strain can be computed
Measures tissue velocity, strain is derived	Strain and strain rate can be measured directly
Influenced by translational motion	Less influenced by translational motion
Image quality less important	Relies on good image quality
Less reproducibility	Greater concordance among observers

Adapted from Biswas M, et al. Two- and three-dimensional speckle tracking echocardiography: clinical applications and future directions. Echocardiography. 2013;30(1):88-105.

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Figures 7A and B Schematic model and dissected heart model showing myocardial fiber arrangements. (A) Depicts the apical and basal loops. The apical loop consists of an outer ascending segment (AS) with oblique counterclockwise fiber orientation and an inner descending segment (DS) with fibers oriented in an oblique clockwise direction. The basal loop covers the upper two-thirds of the apical loop and its fibers are oriented in a circumferential or transverse direction. It can be considered to have two segments: right (RS) and left (LS); (B) Depicts the way the circumferential fibers of the basal loop wrap around the ascending and descending segments.
Reproduced from Buckberg G, Hoffman JI, Nanda NC, et al. Ventricular torsion and untwisting: further insights into mechanics and timing interdependence: a viewpoint. Echocardiography. 2011;28:782-804, with permission from Wiley-Blackwell.

A reasonable understanding of cardiac muscle mechanics is needed to appreciate how 2D STE works. According to the model popularized by Buckberg, et al, the heart is a helix made up of a single myocardial muscle band with fibers of different orientations folded upon itself in 3 layers. This single muscle band has 2 loops, a transverse basal loop which is the middle layer and an oblique apical loop that has two segments. The descending apical segment is the inner layer and twists clockwise while the ascending apical segment is the outer layer and twists counterclockwise. The transverse basal loop wraps around two thirds of the upper ascending and descending segments leaving the lower third of the apex and the ventricular septum free **(Figures 7A and B)**.[20,23,24]

The heart does not move in one direction but in several planes with each cardiac cycle. In systole, long axis motion is shortening from base to apex while radial, transverse and circumferential motions bring the muscle inward. There is also translational motion with the base moving anteriorly. At the same time, the heart rotates with the base moving clockwise and the apex, counterclockwise in systole. In diastole, all these movements are reversed. During the isovolumic contraction period, both the base and apex move in the counterclockwise direction while the ascending apical segment does not move. During the isovolumic relaxation period, both base and apex rotate clockwise with no contraction of the descending apical segment. If there is extended contraction of the descending segment or if contraction crosses over to diastole, (post-systolic contraction or shortening), diastolic filling will be affected because 50% of untwisting motion of the heart or relaxation occurs at this time.[24]

Based on the above movements of the myocardial muscle, parameters of strain (myocardial deformation), strain rate (rate of deformation), and rotational mechanics of rotation, twist and torsion are measured by 2D STE and become useful clinically. 2D STE can also measure these parameters in the other chambers of the heart but are less well investigated.

Strain refers to the percentage thickening or deformation of the cardiac muscles during the cardiac cycle and 2D STE measures 4 types of strain:

1. **Radial strain** (using short axis views).
2. **Transversal strain** (using apical views) that measure thickening of the wall during inward motion and is assigned a positive (+) sign **(Figures 8 and 9)**.
3. **Longitudinal strain** measures the percentage decrease in length as the base predominantly moves toward the apex and is expressed as a negative (–) sign **(Figure 10)**.

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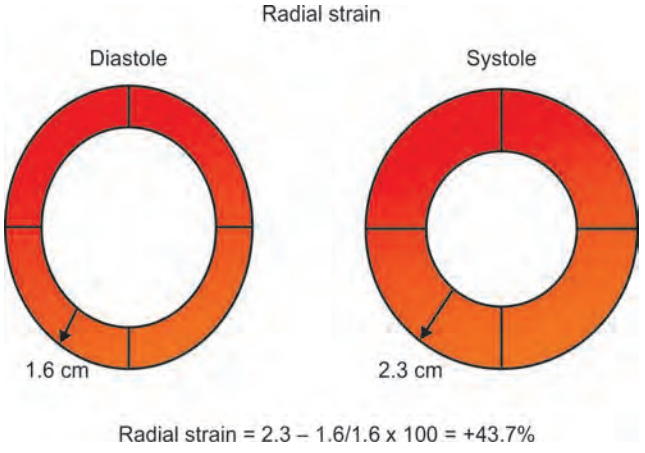


Figure 8 Radial strain shows radial thickening of the myocardium during systole. In the end-diastolic frame on the left, the myocardial thickness is 1.6 cm and increases to 2.3 cm in end systole as depicted on the right; hence, the radial strain will be +43.7%.
Courtesy: Toshiba Medical Systems Europe BV.

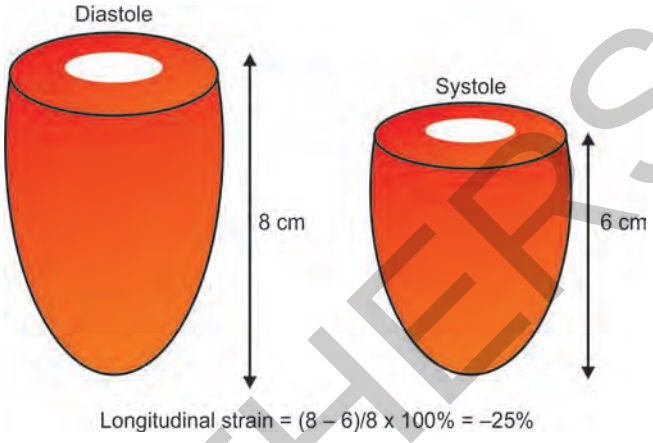


Figure 10 Longitudinal strain shows shortening of ventricular length during systole. The figure on the left denotes end diastole and the one on the right depicts end systole. Note the downward descent of the mitral annulus toward the apex in systole. There is a reduction in length by 2 cm, which is a 25% decrease. As there is a decrease in the longitudinal length, it will be denoted by a negative (–) sign; hence the longitudinal strain will be –25%.

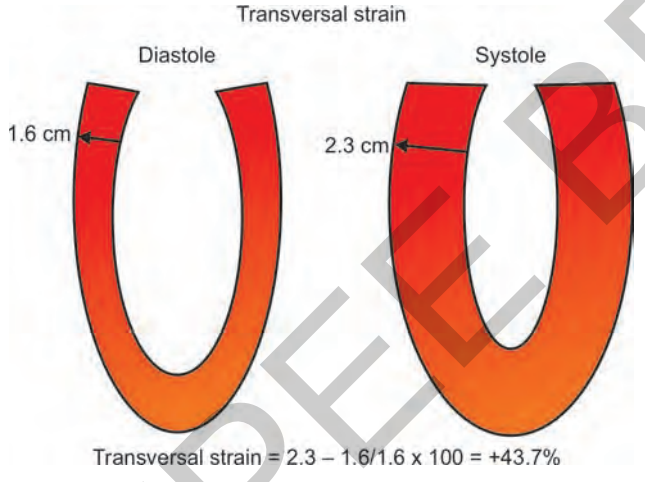


Figure 9 Transversal strain: The calculations are similar to radial strain, except that the measurements are done using apical views.

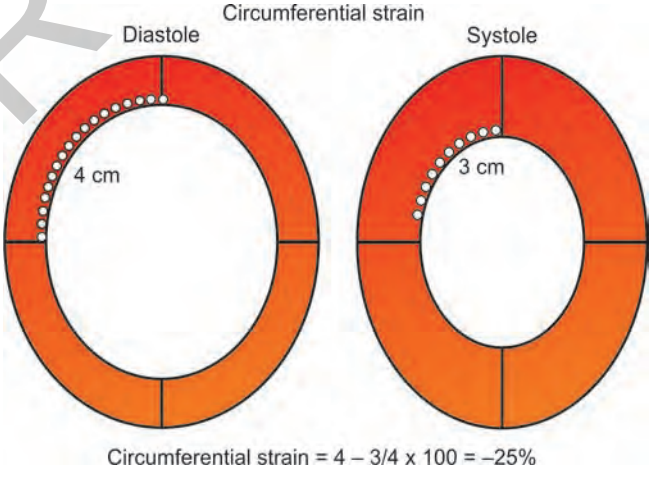


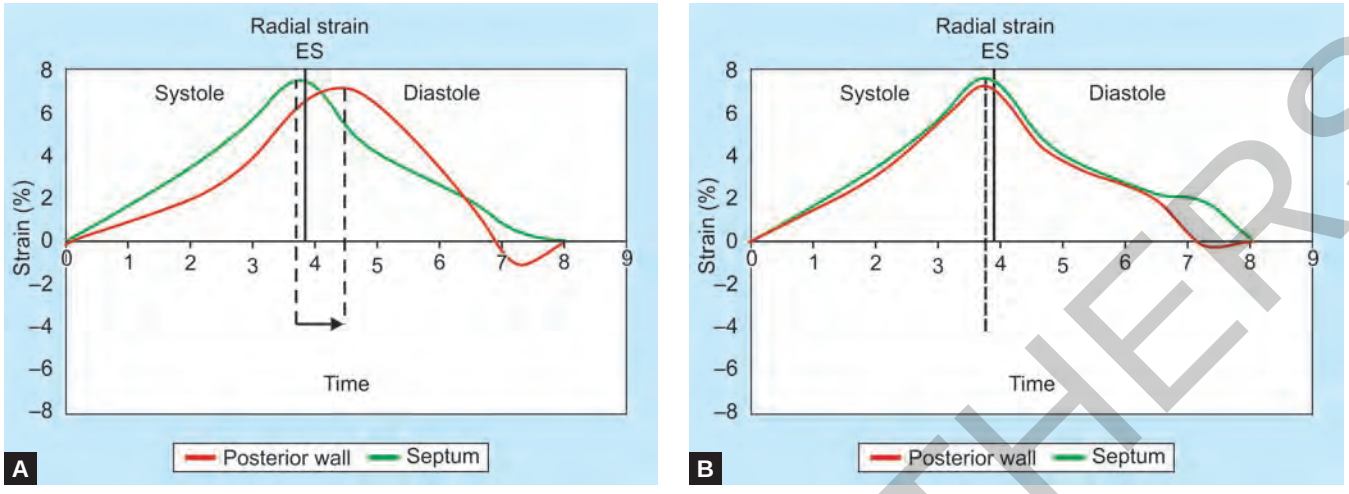
Figure 11 Circumferential strain. This refers to the change in the circumference of each segment as denoted by the dotted yellow line in the figure. There is a 25% reduction in the circumferential length in end-systole from the baseline end-diastole; hence the circumferential strain will be –25%.
Courtesy: Toshiba Medical Systems Europe BV.

4. Circumferential strain measures the change in length along the circular or circumferential perimeter and is assigned a negative (–) sign **(Figure 11)**.

All these strain parameters can be measured individually for each myocardial segment or can be averaged for all the segments to provide global strain. Strain rate is the rate of change of thickness or deformation of the myocardium.

The time from the start of the QRS complex (end diastole) to the time when peak strain occurs (at end systole, end of T wave) coincides with minimum LV volume. Measuring the time difference when peak strain occurs for each muscle segment is also clinically useful as it gives information on dyssynchrony of muscle

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Figures 12A and B Dyssynchronous left ventricular contraction depicted by radial strain. Note the time difference between peak strain of the posterior wall and ventricular septum denoted by the yellow arrow. The peak strain or contraction of the posterior wall is much delayed in comparison with the septum (A). The goal of resynchronization therapy is to get the peak strains (contractions) as close as possible to each other as depicted in (B).
Abbreviation: ES, end-systole.

contraction, as occurs with left bundle branch block. Recognizing this condition, appropriate management such as biventricular pacing can be provided **(Figures 12A and B)**.

For rotational mechanics, the following parameters are measured by 2D STE:

1. Rotation, which is the rotation around a designated long axis line drawn from apex to base through the middle of the LV cavity with clockwise movement given a negative (–) value and counterclockwise, a positive (+) value.
2. Twist measures the algebraic difference between the apex and base rotation.
3. Torsion is twist normalized to the length of the LV cavity. Both twist and torsion can be computed for between any two segments of the myocardium. Likewise, the rate and total duration of rotation can also be calculated **(Figure 13)**.[20]

Some 2D STE applications present tracking results as velocity vectors and this technique is called Velocity Vector Imaging. Each arrow or vector expresses the direction and magnitude of myocardial movement during each cardiac cycle. The vectors are compared along a tracked contour placed over the echo view of the heart **(Figures 14 and 15)**.

Myocardial strain data obtained from 2D STE compare positively with hemodynamics, tissue Doppler, tagged MRI and sonomicrometry studies. Normal values for both strain and rotational mechanics have been published.[20] **Tables 2 and 3** show these values.

Strain and rotational parameters have been described in many cardiac conditions attesting to the clinical usefulness of this technology. **Table 4** presents such a list which is large and may be quite overwhelming. The following general principles should make for a better appreciation of these findings and the tremendous utility of this modality.[20, 25]

- The subendocardial longitudinal fibers are deemed the most susceptible in many disease processes manifested as early deterioration of longitudinal strain and next by radial and circumferential strains.
- Decrease in radial or transversal and circumferential strains are considered more conclusive than wall motion abnormalities in the assessment of ischemic heart disease because the latter are subjectively assessed, and as such are prone to greater interobserver variability.
- Abnormalities of the pericardium lead to aberration of circumferential strain first.
- The hyperactive rotational motion during systole acts as a compensatory process early in the disease causing diastolic dysfunction.
- Untwisting during the post ejection isovolumic interval (isovolumic relaxation period) is hampered early in DD.
- As the diseases become more severe, all the parameters may become further abnormal.

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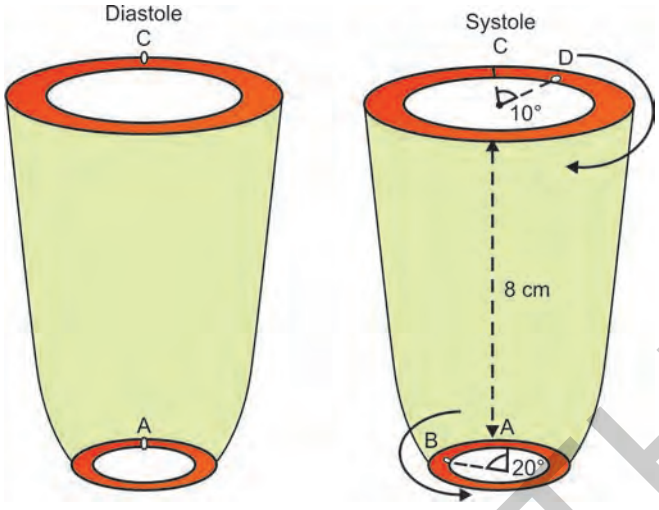


Figure 13 Differential rotational movements of left ventricular apex and the base. In the normal individual, the apex rotates more than the base. By convention, counterclockwise motion is assigned a positive (+) sign and clockwise motion a negative (–) sign. In the above example, the apex rotates 20° in counterclockwise direction from end diastole (point A) to end systole (point B); hence the rotation of the apex will be +20°. As the base rotates at the same time 10° clockwise from point C to D, the rotation of the base will be –10°. "Twist" is calculated as the algebraic difference in the rotation of the apex and base; in other words, how far apart a point in the apex and base move from each other. In the above example, the twist will be apex rotation (20°) minus base rotation (–10°), that is, 20 – (–10) = +30°. Twist can be calculated for any point in the myocardium compared to a reference basal point. "Torsion" is a way of adjusting for the distance of a point of interest from the reference point in the base, as it is expected that the twist will be higher for the segments farther away from the base. Torsion = twist/the distance from the base or distance between any two points that are evaluated. In the above example, the torsion, calculated between apex and base, would be 30/8 = 3.75°/cm. As would be expected, the middle portion of the left ventricle would not show any rotation.

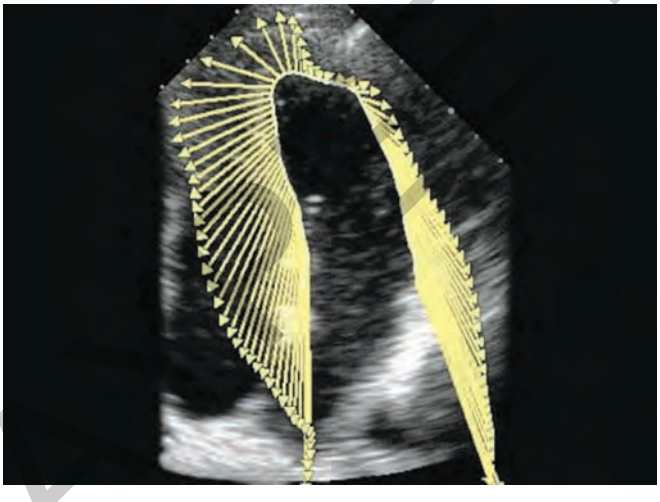


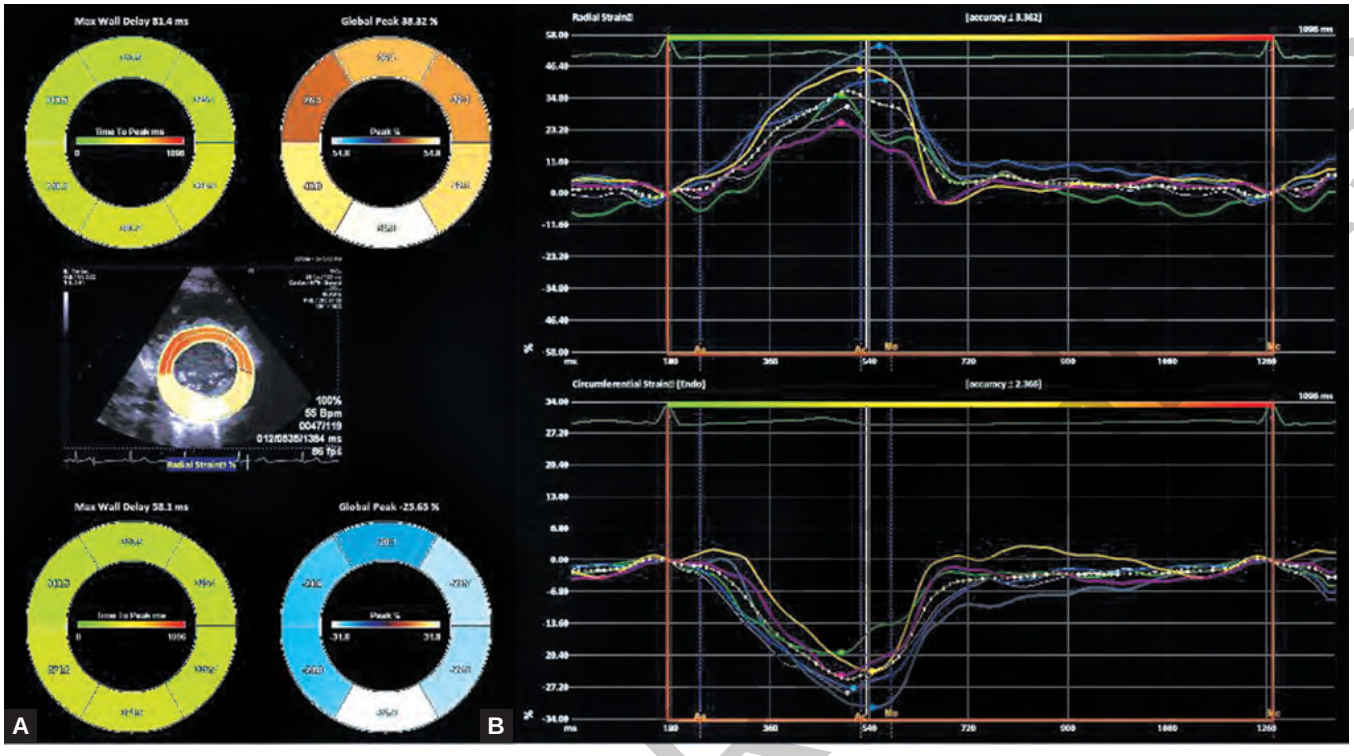
Figure 14 Velocity vector imaging. Apical four-chamber view: the direction of the arrows indicates the direction of the movement of the left ventricular myocardium, and the length of the arrows indicates the velocity of such movement.

2D STE is particularly useful in differentiating the athlete's heart from hypertrophic cardiomyopathy which both present with LV hypertrophy and normal systolic function. **Table 5** shows how these two conditions differ from each other by 2D STE and other parameters.[20]

THREE-DIMENSIONAL SPECKLE TRACKING ECHOCARDIOGRAPHY

The addition of 3D technology has expanded the scope of STE. It eliminates the inherent limitation of 2DE such as out of plane motion when only a thin slice of the myocardium can be imaged whereas a bigger pyramidal volume can be analyzed with 3D STE. One apical volume acquired in a 4-chamber view alone may be enough for the evaluation of all segments and chambers. Real-time acquisition of the motion of

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Figures 15A and B Radial and circumferential strain (A) and longitudinal strain rate; (B) From different segments using velocity vector imaging. The left panel also depicts global peak strain and maximum wall delay.
Courtesy: Siemens ultrasound.

Table 2 Mean percentage strain values by left ventricular region in normal adults

Longitudinal strain	Apical septal 21 ± 4	Mid septal 19 ± 4	Basal septal 17 ± 4	Apical lateral 21 ± 7	Mid lateral 19 ± 6	Basal lateral 19 ± 6
Circumferential strain	Anterior 24 ± 6	Lateral 22 ± 7	Posterior 21 ± 7	Inferior 22 ± 6	Septal 24 ± 6	Anteroseptal 26 ± 11
Radial strain	Anterior 39 ± 16	Lateral 37 ± 8	Posterior 37 ± 17	Inferior 37 ± 17	Septal 37 ± 19	Anteroseptal 39 ± 15

Source: Hurlburt HM, Aurigemma GP, Hill JC. Direct ultrasound measurement of longitudinal, circumferential, and radial strain using 2-dimensional strain imaging in normal adults. Echocardiography. 2007;24:723-31.

Table 3 Normal rotation and torsion in young adults

Peak apical rotation (°)	10.1 ± 1.9
Peak apical rotation rate (°/s)	61.6 ± 25.3
Peak basal rotation (°)	4.9 ± 2.0
Peak basal rotation rate (°/s)	44.2 ± 17.8

Source: Takahashi K, Al Naami G, Thompson R. Normal rotational, torsion and untwisting data in children, adolescents and young adults. J Am Soc Echocardiogr. 2010;23:286-93.

basal and apical segments is possible by 3D STE while with 2D STE; information is gathered from 2 short axis views taken at 2 different time points which would be altered by different heart rates and thus, results in unreliable determination of rotational parameters. A joint assessment of longitudinal and circumferential strains, termed area strain, can also be performed with 3D while this is not possible with 2D **(Figures 16A and B)**.[25-27]

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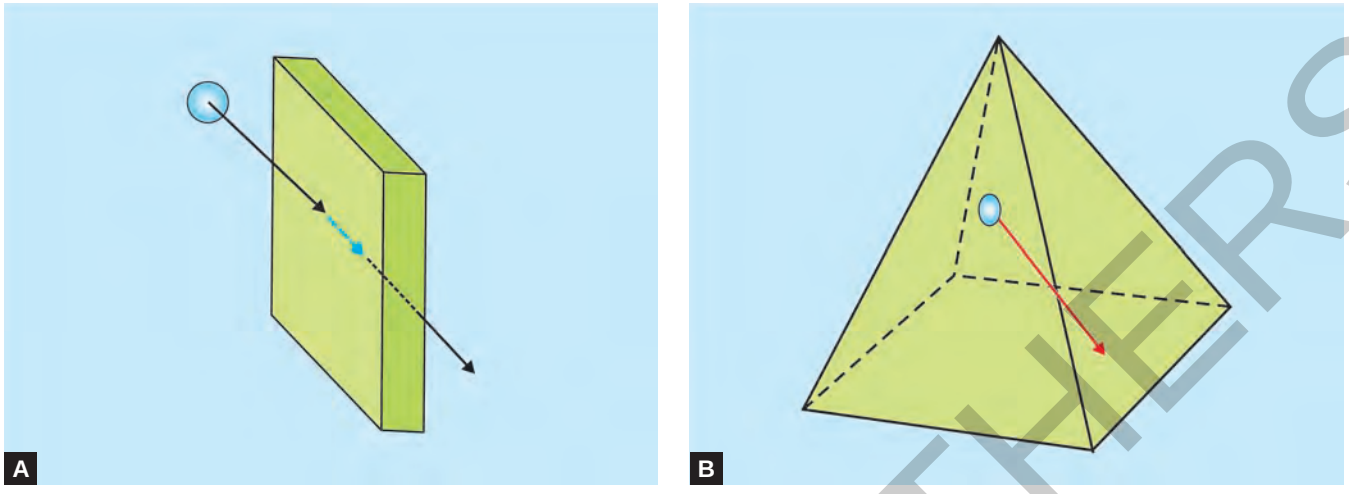
TABLE 4 Clinical conditions where two-dimensional speckle tracking is useful

1. Myocardial ischemia	Reduction in strain by 2D STE more objective and accurate than the traditional visual method of assessing WMA
	Longitudinal, radial, and circumferential strain reduced in ischemic areas in coronary artery disease
	Postsystolic thickening (deformation), detected by radial strain correlates with the severity of ischemia
2. Myocardial infarction	2D STE successful in differentiating transmural from subendocardial infarction by showing lower circumferential strain in the former
	Reduced subendocardial LV twist also noted in patients with ST-segment elevated myocardial infarction
	Decreased LV torsion and segmental longitudinal strain predicts progressive
	LV dilatation after myocardial infarction
3. Myocardial viability	Strain measurements by 2D STE more objective and accurate than visual WMA for assessment of myocardial viability during low-dose dobutamine stress echocardiography. 2D STE differentiates active contraction from passive motion due to tethering
4. Heart failure with normal LVEF	Reduced and delayed LV untwisting—at rest and exercise
5. Cardiac resynchronization therapy (CRT)	Combining longitudinal strain from TDI velocity with 2D STE radial strain may help in predicting response to CRT
	Longitudinal strain delay index (calculated from the difference between peak and end-systolic strain) of >25% predicts response to CRT (sensitivity 95%, specificity 83%)
	Speckle tracking and resynchronization (STAR) study showed that radial and transversal strain were better than longitudinal and circumferential strain in predicting LVEF response and long-term survival after CRT
	Lack of dyssynchrony before CRT by 2D STE radial strain associated with death or hospitalization for heart failure
6. Stress cardiomyopathy	Impaired longitudinal strain noted particularly in apical and midventricular segments
7. Restrictive cardiomyopathy	Impaired longitudinal deformation and twist mechanics are noted
8. Constrictive pericarditis	Impaired LV circumferential deformation and torsion
9. Detection of rejection and coronary stenosis in heart transplant patients	Sudden reduction of ≥15% in global radial strain associated with acute rejection
	Decrease in strain and strain rate at rest and with dobutamine stress echo also useful to detect significant coronary stenosis
10. Early detection of chemotherapy-induced cardiotoxicity	Reduction in radial strain may occur before reduction in LVEF and associated with histologic changes
11. Detection of subclinical diseases/ early myocardial involvement	Reduction in strain may occur before changes in LVEF in systemic hypertension, diabetes mellitus, systemic sclerosis, amyloidosis, Duchenne's muscular dystrophy, and Kawasaki syndrome
12. Valvular heart disease	Decreased radial, circumferential, and longitudinal strain in patients with severe aortic stenosis and normal LVEF. Long-term follow-up after valve replacement showed significant improvement with no change in EF
	Reduced preoperative 2D STE longitudinal strain in the ventricular septum (apical four-chamber view) predicts a postoperative LVEF decrease of ≥10% in patients with chronic severe mitral regurgitation
13. Congenital heart disease	Atrial septal defect—basal clockwise rotation during systole is reduced
	Tetralogy of Fallot—right ventricular global longitudinal strain and strain rate is decreased significantly

Abbreviations: 2D, two-dimensional; EF, ejection fraction; LV, left ventricle; LVEF, left ventricular ejection fraction; TDI, tissue Doppler imaging; STE, speckle tracking echocardiography; WMA, wall motion abnormalities.

Source: Biswas M, et al. Two- and three-dimensional speckle tracking echocardiography: clinical applications and future directions. Echocardiography. 2013;30(1):88-105.

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Figures 16A and B Advantage of three-dimensional speckle tracking echocardiography over the two-dimensional (2D) technique. (A) As 2D echocardiography represents only a thin slice through the cardiac structures, it is easy for the speckle particle to move out of the scanning plane as the heart moves, making it difficult or impossible to track the same speckle during the cardiac cycle; (B) On the other hand, with the three-dimensional (3D) technique, a much larger pyramidal-shaped section is obtained, making it more difficult for the speckle particle to move out of the 3D data set.
Courtesy: Toshiba Medical Systems Europe BV.

TABLE 5 Differentiation of athlete's heart from hypertrophic cardiomyopathy using speckle tracking

Athlete's heart	*Hypertrophic cardiomyopathy*
Normal longitudinal and other types of strain	Decreased longitudinal strain
Increased LV EDV	Decreased LV EDV
Decreases after deconditioning for 3 months	No change with deconditioning
Increased LV twist	Delayed LV untwisting
Increased early LA strain rate	Reduced LA strain and strain rate
No postsystolic thickening	Postsystolic thickening present

Abbreviations: EDV, end-diastolic volume; LA, left atrium; LV, left ventricle.
Reproduced with permission from Biswas M, et al. Two- and three-dimensional speckle tracking echocardiography: clinical applications and future directions. Echocardiography. 2013;30(1):88-105.

SUMMARY

A patient with dyspnea and normal LV systolic function may either have diastolic heart failure or a non cardiac cause of dyspnea. When the transmitral flow pattern is normal, this may reflect either normal diastolic function, or pseudonormal filling pattern, which does reflect significant DD. Thus, multiple echo-Doppler parameters (LV mass, LA volume, TDI, pulmonary veins and pulmonary artery pressures) must be integrated to establish if heart failure is present or not.

There is a need to reconcile all clinical information with the echocardiographic findings and learn the same on simulation **(Figures 17 to 19)**. A small LA often excludes a diagnosis of DHF, as long as echocardiography is performed prior to diuresis or BP lowering in a patient presenting with dyspnea. Concentric LVH or remodeling and wall motion abnormalities are clues that underlying DD may be present. A young, healthy patient, on the other hand, may have E > A, but this pattern likely reflects



Figure 17 The transthoracic echo probe simulator position to learn left ventricular diastolic function

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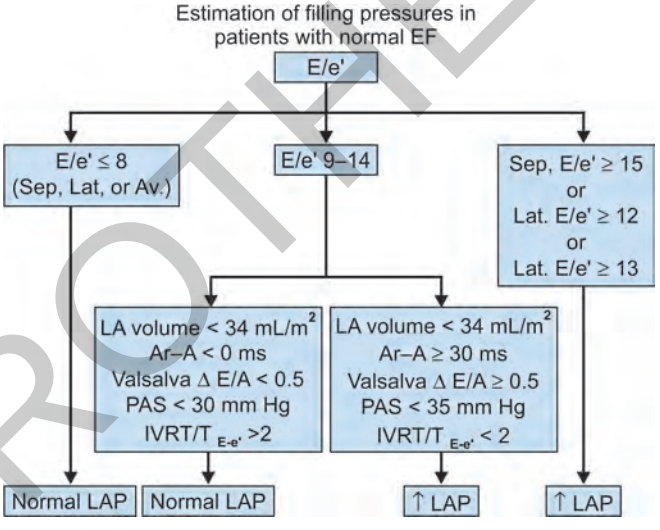


Figure 18 Holding the probe in the right manner is essential for preventing probe related complications. Practice on simulator is best



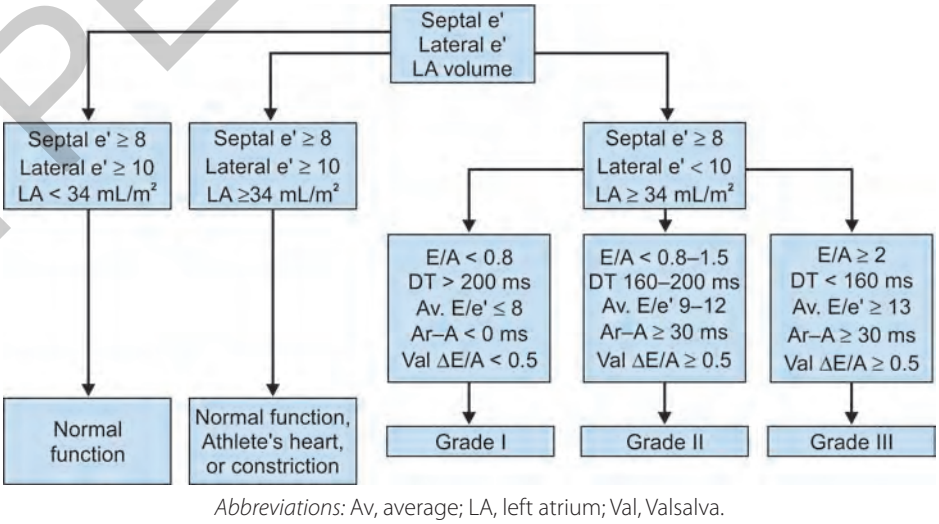
Figure 19 The exact position of the transesophageal echocardiography probe on the simulator is learnt best in experienced hands.

Flow chart 1 An integrated approach to the assessment of left ventricular diastolic function: normal LV ejection fraction. As recommended in the current guidelines, use of multiple echo Doppler parameters results in a more accurate assessment of left ventricular (LV) diastolic function than using any single echo Doppler parameter in isolation. In the patient with normal LV ejection fraction (EF), it is reasonable to start with early transmitral diastolic velocity/tissue Doppler early diastolic velocity (E/e'), as it can be difficult to discern whether a patient with preserved LVEF has impaired or normal LV relaxation. Following E/e', other echo Doppler variables are added to result in an accurate assessment of LV diastolic function.



Reproduced with permission from Nagueh SF, Appleton CP, Gillebert TC, et al. Recommendations for the evaluation of left ventricular diastolic function by echocardiography. J Am Soc Echocardiogr. 2009;22(2):107-33.

Flow chart 2 Practical approach to grading diastolic dysfunction



Abbreviations: Av, average; LA, left atrium; Val, Valsalva.

Source: Nagueh SF, Appleton CP, Gillebert TC, et al. Recommendations for the evaluation of left ventricular diastolic function by echocardiography. J Am Soc Echocardiogr. 2009;22(2):107-33.

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normal diastolic function. When the transmitral flow shows E < A, impaired relaxation with normal LA pressures (grade I DD) is usually present. With a normal or pseudo normal pattern, proceeding to TDI and measuring E′ velocity to calculate E/e′ often distinguishes normal from pseudonormal filling pattern. Valsalva maneuver may also be used to distinguish normal from pseudonormal filling; however, TDI is often more practical and reliable. Other echo-Doppler variables can be used additionally if the results are still indeterminate. **Flow chart 1** provides an algorithm for the estimation of LV filling pressures in patients with normal estimate filling pressure.[4]

In a patient with low LVEF, diastolic dysfunction is almost always present. One does not need to do an elaborate evaluation of diastolic function but the goal is to approximate LV filling pressures which has a direct bearing for prognosis and treatment.

A scheme on how to grade diastolic dysfunction is presented in **Flow chart 2**.[4] Increasing severity of DD relates to poor prognosis in spite of normal LVEF.

Transmitral flow Doppler remains central to the diagnosis of DD in the presence of normal LVEF, in combination with the less load dependent modality of TDI. They are more practical and reliable to use than pulmonary venous flow, flow propagation velocity or the Valsalva maneuver. The emergence of 2D and 3D STE add incremental value to the definite assessment of many cardiac conditions with both preserved and poor LVEF, decreasing errors in the evaluation of DHF.[28]

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