

Doppler Tissue Imaging for the Assessment of Left Ventricular Diastolic Function: A Systematic Approach for the Sonographer

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Mitral annular Doppler tissue imaging (DTI) has been proven to be useful in estimating left ventricular (LV) diastolic filling pressures, and can be applicable to clinical use in adult cardiology.¹⁻³ Prior studies have highlighted the technical aspects of DTI and the reproducibility of its measurements; however, recommendations and a systematic approach designed to help sonographers obtain accurate and reproducible Doppler tissue recordings have not been published.⁴⁻⁶ Therefore, this article will: (1) discuss the potential role for DTI in the assessment

of diastolic function combined with standard transmitral Doppler recordings; (2) review prior studies of DTI in the estimation of LV filling pressures; (3) highlight technical issues associated with DTI; and (4) propose a systematic approach for the sonographer to obtain accurate and reproducible Doppler tissue tracings.

CME STATEMENT

The American Society of Echocardiography (ASE) is accredited by the Accreditation Council for Continuing Medical Education (ACCME) to sponsor continuing medical education for physicians. The ASE designated this educational activity for 1 hour of Category 1 credit of the American Medical Association Physicians' Recognition Award. The ASE adheres to ACCME standards regarding industry support of continuing medical education. Disclosures of faculty and commercial sponsor relationships, if any, have been indicated.

Target Audience:

Participation should include persons from the fields of cardiac sonography, cardiovascular anesthesiology, cardiovascular medicine, cardiovascular surgery, pediatric cardiology, neurology, and nursing, as well as medical residents/fellows and students.

Educational Objective:

After reading this article, the participant should be able to do the following:

1. Discuss the role of Doppler tissue imaging (DTI) for the assessment of diastolic function
2. Understand the basics of DTI and its relation to left ventricular myocardial relaxation
3. Discuss the technical issues and limitations associated with blood and DTI
4. Adapt a systematic approach for acquiring accurate and reproducible Doppler tissue tracings

The estimated time for this CME activity is approximately 1 hour.

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BEYOND THE MITRAL E/A RATIO: THE CLINICAL NEED FOR ADDITIONAL DATA

Limitations of Standard Doppler Velocities

The assessment of LV filling pressures such as left atrial pressure (LAP) and its surrogate, pulmonary capillary wedge pressure (PCWP), is of great importance to the clinician. If filling pressures are high, this may be an indication that dyspnea may be caused in part by pulmonary congestion. If filling pressures are low, this may help explain symptoms of low cardiac output or, in an extreme case, syncope. Therefore, a noninvasive technique that could simply and reliably predict filling pressures would be invaluable not only in diagnosis, but more importantly, in tailoring therapy.

In patients with depressed LV ejection fraction (EF), it has been well established that transmitral Doppler variables can be used to accurately predict PCWP.^{3,7-11} However, the transmitral flow variables predict filling pressures less reliably in patients with normal EF ($\geq 50\%$), who comprise approximately half of all patients with heart failure.^{3,9-12} Given these limitations, additional echocardiographic data are often needed.

Principles of Transmitral Velocity Curves

In normal sinus rhythm, diastolic flow from the LA to the LV across the mitral valve has two components: the E-wave, which reflects early diastolic filling; and the A-wave in late diastole, which is related to flow caused by atrial contraction. These transmitral velocities are determined by the transmitral pressure gradient, which in turn is influenced by both the rate of early LV diastolic relaxation and the level of LAP. The transmitral E-wave velocity, therefore, reflects the early diastolic pressure gradient

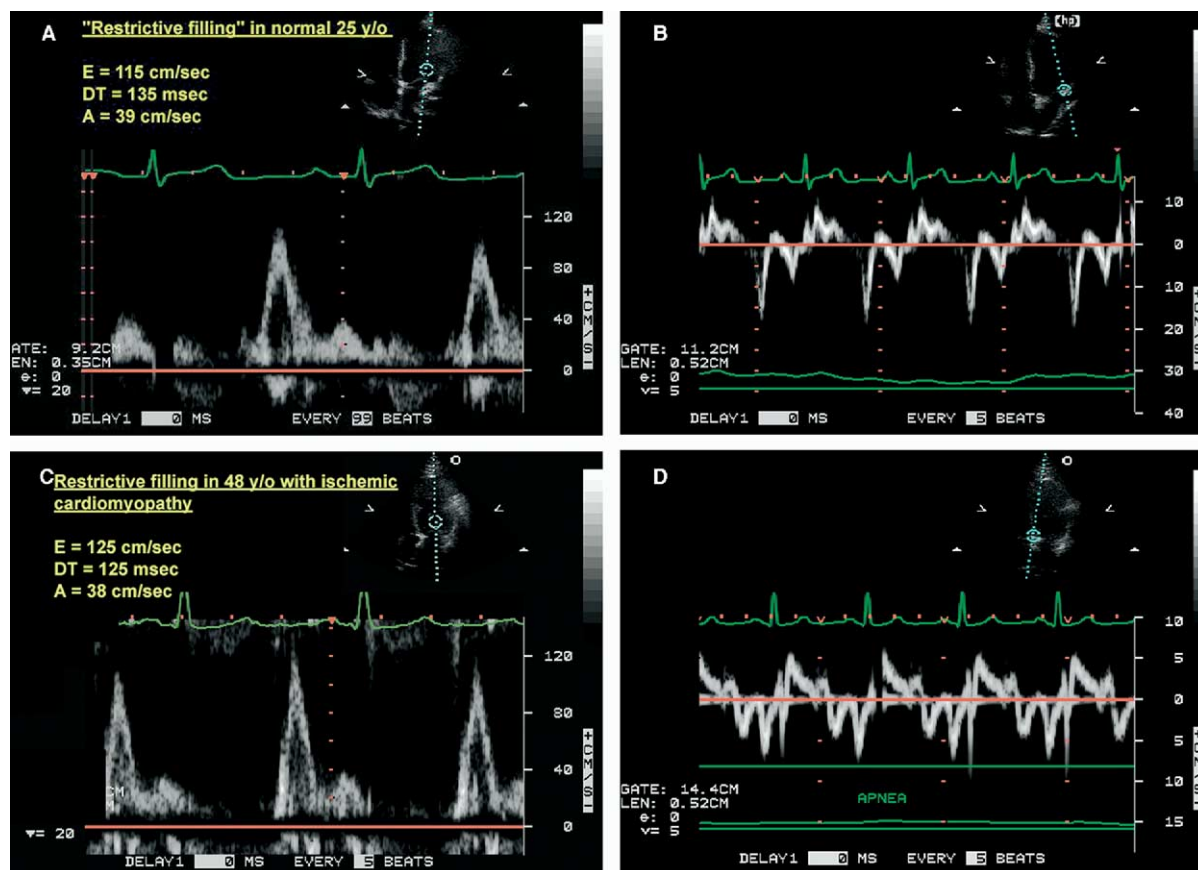


Figure 1 Restrictive filling patterns in normal and disease states. **A**, Restrictive filling pattern obtained in a healthy, 25-year-old man with no evidence of structural heart disease. Tall E-wave and rapid deceleration represent vigorous early diastolic suction and excellent left ventricular (LV) compliance. **B**, In same patient, lateral Doppler tissue imaging (DTI) was obtained during end-expiratory apnea. Annular E' measures 16 cm/s; E/E' ratio = 7 consistent with normal LV filling pressures. **C**, Restrictive filling pattern obtained in a 48-year-old man with ischemic cardiomyopathy. Tall E-wave, rapid deceleration time, and truncated A-wave represents elevated left atrial pressure as a result of abnormal LV relaxation and compliance. **D**, In same patient, septal DTI was obtained during end-expiratory apnea. Annular E' measures 4 cm/s; E/E' ratio = 31 consistent with highly elevated LV filling pressures.

between the LA and LV, which may be increased by elevated LAP, vigorous diastolic suction in normal LV filling, or both (Figure 1). Alterations in the pattern of these inflow variables allow understanding of ventricular diastolic function and prediction of prognosis.

Although some advocate the Valsalva maneuver as a means of differentiating pseudonormal mitral E/A ratios from normal ones¹³ (Figure 2), this maneuver has limitations. It is difficult to perform correctly (for the sonographer and the patient) and cannot be performed easily in patients who are critically ill and intubated. Additional help for the assessment of diastolic function may be furnished by analysis of pulmonary vein flow velocities. However, acquiring accurate pulmonary vein Doppler can be technically challenging for the sonographer because of poor temporal resolution caused by longer processing

time of color Doppler and limitations of 2-dimensional image quality, particularly in the far field of the ultrasound image. In contrast, like transmitral Doppler, annular DTI is easy to perform because it is not particularly dependent on image quality or timely processing of the spectral Doppler signal. Therefore, the sonographer, with a small amount of instruction, can obtain high-quality Doppler tissue tracings in a short period of time.

Relation of the DTI Waveforms to Cardiac Motion and Physiology

The annular DTI waveforms obtained from the apical 4-chamber view display direction and velocity of the annulus as it travels throughout the cardiac cycle. During systole, the annulus moves toward the apex resulting in a positive waveform on the Dopp-

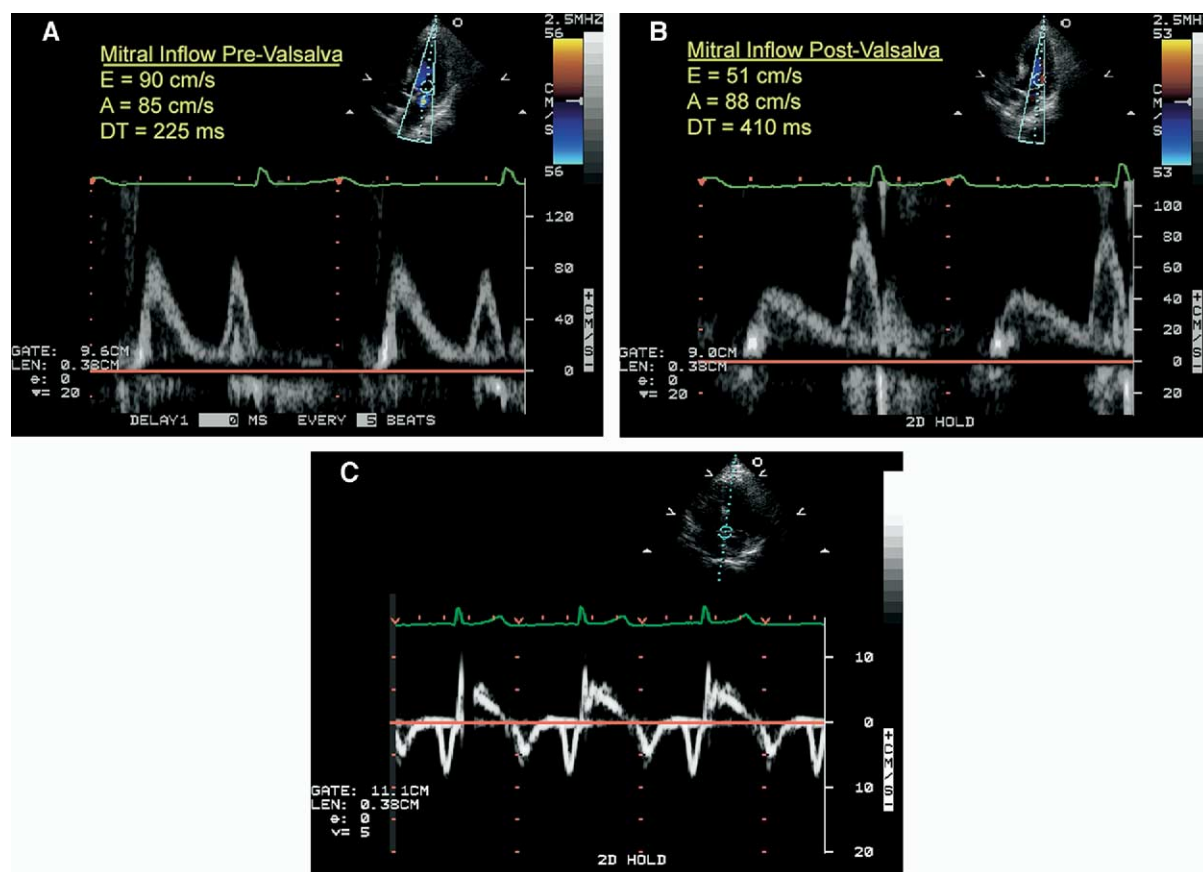


Figure 2 Effects of Valsalva maneuver on suggested pseudonormal filling pattern. **A**, Transmitral Doppler obtained from a patient with severely reduced left ventricular (LV) systolic function (ejection fraction = 25%). The Doppler profile appears normal with an E/A ratio > 1 and normal deceleration time. **B**, In same patient, Valsalva maneuver unmasks underlying abnormality. The E-wave velocity and E/A ratio are significantly decreased, and deceleration time is increased; A-wave velocity is unchanged. Valsalva maneuver unmasked pseudonormal filling indicating elevated filling pressures. It is important to note that in normal filling, peak mitral E- and A-wave velocities decrease proportionally and E/A ratio does not change significantly with Valsalva maneuver. **C**, In the same patient, septal annular Doppler tissue imaging was obtained during end-expiratory apnea. The annular E' measures 5 cm/s; E/E' ratio = 18 consistent with elevated LV filling pressures.

ler display. There is one major systolic velocity (S'). During diastole, the annulus is displaced first toward the base by the effects of ventricular relaxation, and again by atrial systole. During normal in sinus rhythm, the diastolic DTI waveform has two major components: (1) the early velocity (E'); and (2) the late velocity (A') (Figure 3).

INITIAL OBSERVATIONS AND VALIDATION STUDIES: THE E' , E/E' RATIO, AND A' VELOCITIES

Noninvasive Estimation of LV Diastolic Pressure and Relaxation

Isaaz et al¹⁴ first reported the use of DTI by quantitating high-amplitude, low velocities of the posterior

wall. However, the use of this Doppler technique did not come into widespread clinical use until the late 1990s. The E/E' ratio (mitral E wave divided by annular tissue E' wave) has been validated as a reliable index for the estimation of PCWP.¹⁻³ The annular Doppler tissue E' wave reflects the velocity of ventricular lengthening in early diastole and is related to time constant of relaxation (τ) and elastic recoil. An LV with slower relaxation will, therefore, have a lower E' velocity. In this way, the E' velocity can correct the mitral E wave velocity for the influence of ventricular relaxation.

For example, a 65-year-old patient with hypertensive heart disease and dyspnea may have a normal-appearing mitral E-wave velocity and E/A ratio. It is not immediately clear, however, that this represents elevated LAP; annular DTI obtained from the septal or lateral annulus can be

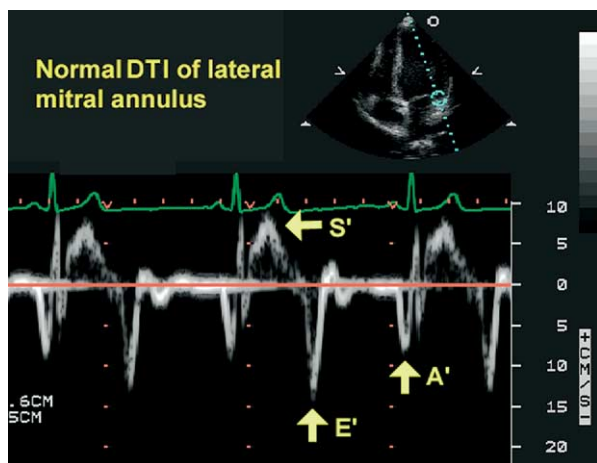


Figure 3 Normal Doppler tissue imaging (DTI) waveform obtained at lateral mitral annulus in healthy patient during end-expiratory apnea. The spectral Doppler profile is characterized by single positive waveform above baseline (S') and negative waveforms in early (E') and late (A') diastole.

very helpful in this case by calculating the E'/E' ratio. A low E'/E' ratio (<8) usually indicates normal LAP (<10 mm Hg); conversely, a high E'/E' ratio (>15) usually indicates elevated LAP (>15 mm Hg). E'/E' ratios between 8 and 15 obtained from the septal annulus have been reported to be less reliable for the estimation of LAP.³ Under these circumstances, the sonographer should ascertain other echocardiographic variables (ie, Valsalva maneuver, pulmonary vein-S/D ratio, pulmonary vein atrial reversal velocity, and mitral A-wave duration/pulmonary vein A-duration ratio) attempting to demonstrate elevated filling pressures.

Clinical Application of DTI A' Velocity

Although mitral annular Doppler tissue A' velocity correlates positively with the first derivative of LAP (LA dp/dt) and inversely with left ventricular end diastolic pressure (LVDP) in animal experiments,¹⁵ relatively less is known about the clinical application of the annular Doppler tissue A' velocity. A recent study demonstrated that mitral annular A' velocity less than 5 cm/s was the most powerful predictor of cardiac death or hospitalization for worsening heart failure compared with clinical, hemodynamic, and other echocardiographic variables.¹⁶ Importantly, this study demonstrated a significant negative correlation ($r = -0.94$) between the peak mitral annular A' velocity and mean PCWP in patients with different mitral filling patterns (ie, delayed relaxation, normalized, and restrictive) and LV systolic dysfunction.

A modest correlation between the peak mitral annular A' velocity and both LA systolic fractional

Table 1 Potential factors that may influence annular Doppler tissue imaging diastolic velocities

1. Sample volume size and positioning
2. Doppler gain
3. Mitral annular calcification
4. Phase of respiration
5. Beam alignment

area change and fractional volume change has been shown.¹⁷ The results of these studies suggest that DTI A' velocity may prove to be a valuable tool for quantitating atrial function, predicting clinical outcomes, or both.

TECHNICAL ISSUES ASSOCIATED WITH DTI

A Sonographer's Approach to Optimal DTI Tracings

To increase accuracy and reproducibility of annular DTI, the sonographer should be aware of certain pitfalls, which may affect or influence the Doppler signals (Table 1). Proper sample volume placement at the annulus is critical to produce accurate Doppler tissue tracings. Subtle changes in sample volume positioning outside the annulus (Figure 4) can highly influence the Doppler tracings. Like all Doppler tracings, gain can affect the peak Doppler tissue velocities (Figure 5). Therefore, gain should be minimized to allow for clear Doppler signals with minimal background noise. The interest in DTI and recognized increasing clinical use of the E'/E' ratio for estimation of LAP has led to the addition of DTI presets being available in the latest generation ultrasound equipment. If a preset is not available, the sonographer should consult the manufacturer.

DTI Annular Site

Although the E'/E' ratio was the single best parameter for predicting mean left ventricular diastolic pressure (LVDP) (a surrogate of LAP) for all levels of systolic function, Ommen et al³ demonstrated that E'/E' ratio using the medial annulus correlated better with mean LVDP. However, a recent publication showed that the lateral annular E' velocities used for the E'/E' ratio correlated best with LAP when the EF is greater than 50%; if the EF was less than 50%, a combination of conventional and refined Doppler indices may be used without significant error.¹⁰

Phase of Respiration

The phase of respiration affects DTI recordings in view of breathing-associated shifts in cardiac position. To our knowledge, only 3 studies reported the use of end-expiratory apnea as a standard

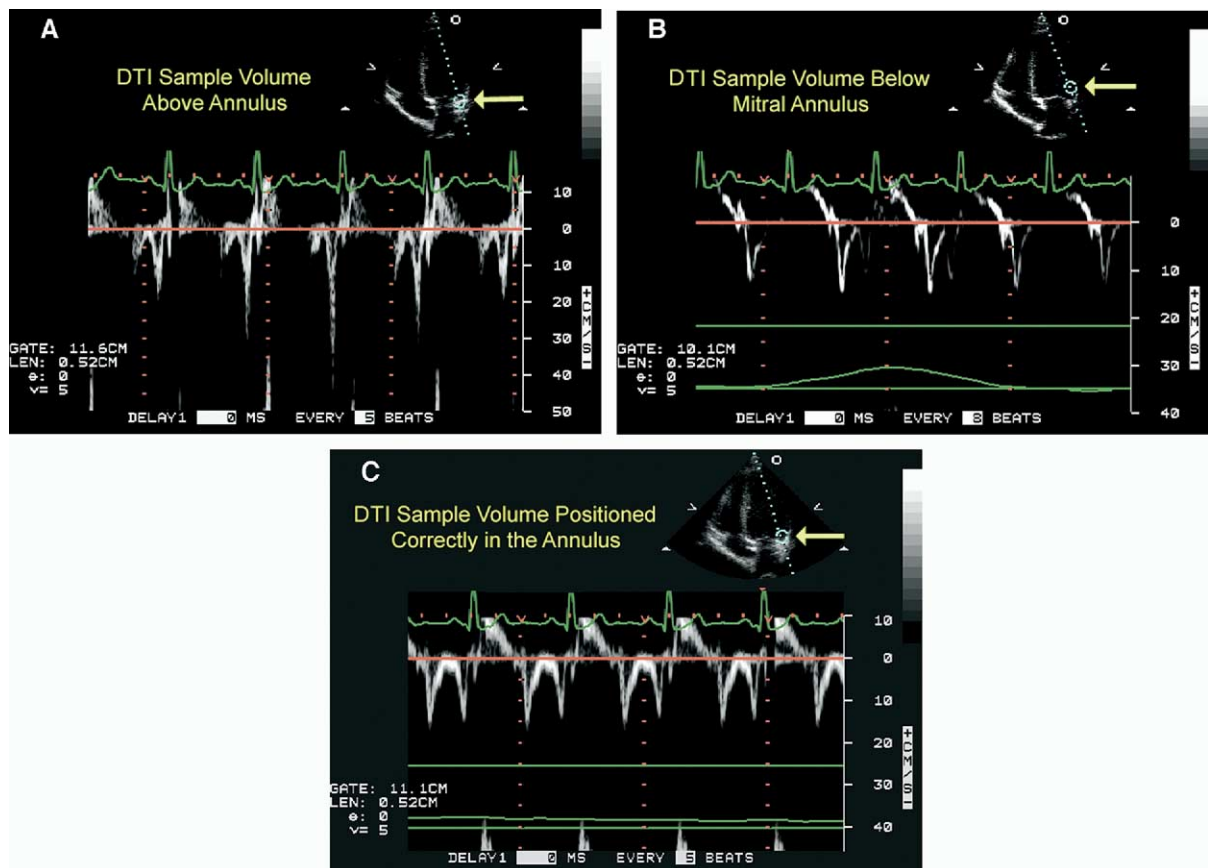


Figure 4 Effects of sample volume position on Doppler tissue imaging (DTI) velocities and tracings. Doppler waveforms obtained from same patient. **A**, Doppler waveforms obtained with the sample volume located slightly above (on the apical side) lateral mitral annulus during normal respiration. Tracings are nonuniform and, therefore, difficult to measure. Note significant differences in peak E' and A' velocities from beat-to-beat. **B**, Doppler waveforms obtained slightly below (on ventricular side) lateral annulus during normal respiration. Doppler tracings are nonuniform, faint, and difficult to measure. **C**, Doppler waveforms with proper sample volume placement at lateral mitral annulus during end-expiratory apnea. Doppler waveforms are uniform and consistent, with no beat-to-beat variation of peak diastolic velocities. This permits easy, consistent measurement.

when obtaining annular DTI recordings.^{3,5,18} A recent publication has demonstrated significant effects on the E' velocity at the septal annulus during respiration (mean $35 \pm 18.0\%$, range 10%-71%) in patients with constrictive pericarditis.¹⁹ Preliminary data in patients with EF greater than 50% suggests that significant differences in peak E' velocities measured at the lateral mitral annulus occur during different phases of respiration (mean $27 \pm 15\%$, range 0%-71%).²⁰ This variation is likely caused by a rapid shift in the heart position during respiration over a fixed Doppler sample volume, inaccurately recording the true annular velocities (Figure 6), resulting in an overestimation or underestimation of the E/E' ratio. When possible, the sonographer should obtain lateral DTI during end-expiratory apnea, to improve accuracy and consistency of the peak DTI velocities.

Sample Volume Size and Location

The septal annulus has been reported to have less excursion, resulting in lower velocities than the lateral annulus.² Therefore, different sample volume size should be used for different annular location (ie, lateral vs septal; septal annular imaging may improve with an approximate 3.5 mm sample volume, and lateral annular imaging improved with an approximate 5.0 mm sample volume). The rationale behind using different sample volume size is that increased lateral annular motion may require a larger sample volume to record the annular velocities properly. To optimize all components of the DTI signal, sample volume size should be proportional to annular motion and not limited to either septal or lateral annulus. Dumesnil, et al¹⁸ showed there was no variation in the E' and E/E' ratio when the sample

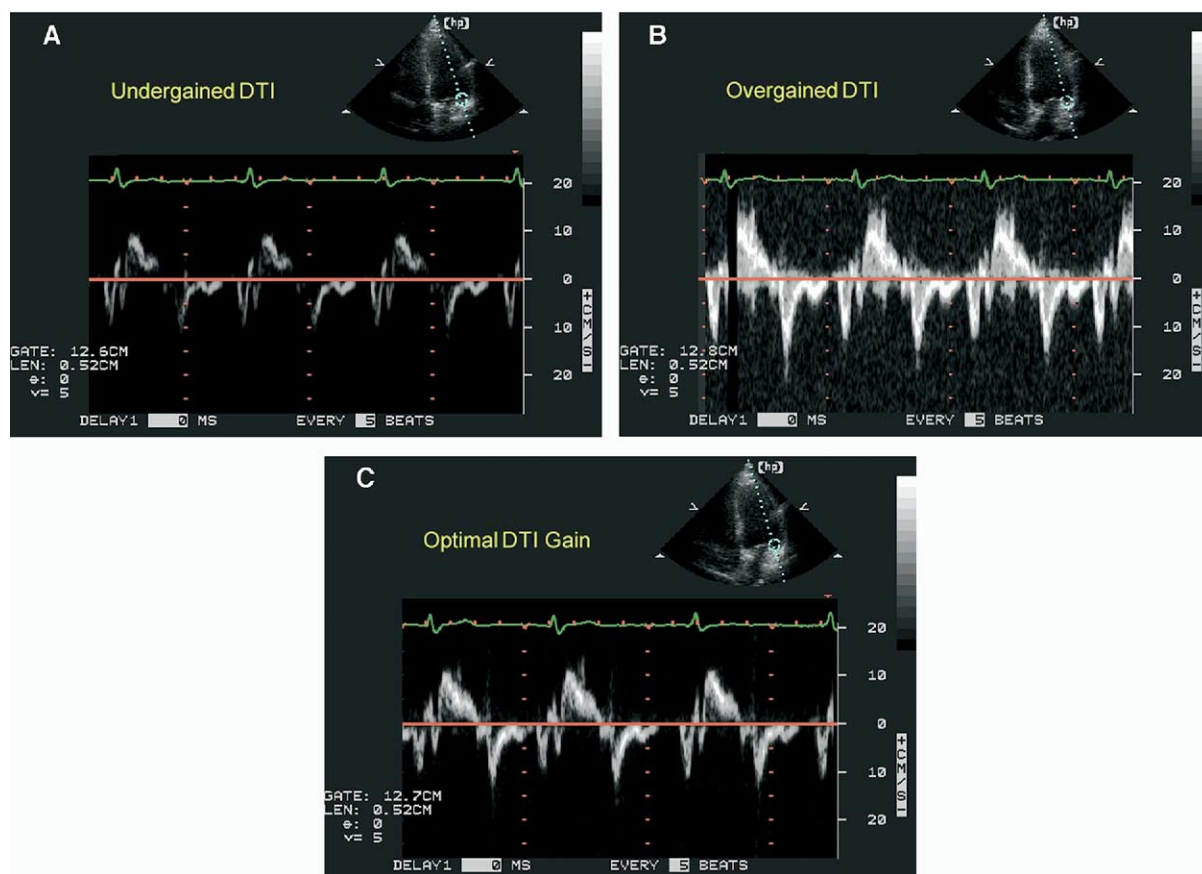


Figure 5 Effects of gain on Doppler tissue imaging (DTI) obtained from the same patient, measured at the lateral mitral annulus. **A**, Decrease in Doppler gain, resulting in marked underestimation of peak annular velocities; peak E' velocity = 9 cm/s. **B**, Effects of increased Doppler gain. Significant overestimation of peak annular velocities is present; peak E' velocity = 18 cm/s. Waveforms are coarse, and would likely result in overestimation of peak annular velocities. **C**, Doppler gain is properly minimized to allow for clear signals with minimal background noise; TDI tracings demonstrate clear, consistent peak velocities, which can be appropriately measured; peak E' velocity = 13 cm/s.

volume was placed at the lateral annulus and reduced from 5 mm to 1.5 mm, respectively. However, A' and E'/A' ratio varied significantly depending on sample size and location.

Mitral Annular Calcification

Mitral annular calcification (MAC) may influence annular motion by reducing its excursion. Recent work by Soeki et al²¹ has shown that severe MAC is associated with elevated transmitral inflow velocities in the absence of significant valvular stenosis, and low E' velocities. Thus, for patients with extensive MAC, the E'/E' ratio may be elevated. Whether elevation in this ratio reliably reflects elevated LAP has not been completely established by hemodynamic validation studies. Until further data is furnished on MAC and the estimation of early diastolic filling pressures, the sonographer should use caution when reporting the E'/E' ratio.

Effects of Aging on DTI

Normative values need to be established to interpret DTI, which can separate disease states from the healthy state (Table 2). DTI indices and the mitral E/A ratio are both influenced by age. Initially, researchers noted in small studies that age appeared to have an inverse correlation with Doppler tissue velocities.^{1,2,22-25} The effects of aging on the Doppler tissue E' and E'/E' ratio were demonstrated in a large sample of healthy participants of varying ages by Tighe et al²⁶ and later confirmed by Munagala et al.²⁷ The E' velocity decreased and the A' velocity varied significantly with age. They demonstrated that the age-related decline in the E' velocity in control subjects affected the E'/E' ratio. In fact, in one study, which suggests elevated LAP (E'/E' ratio > 10 detected a mean PCWP > 15 mm Hg),² E'/E' ratios

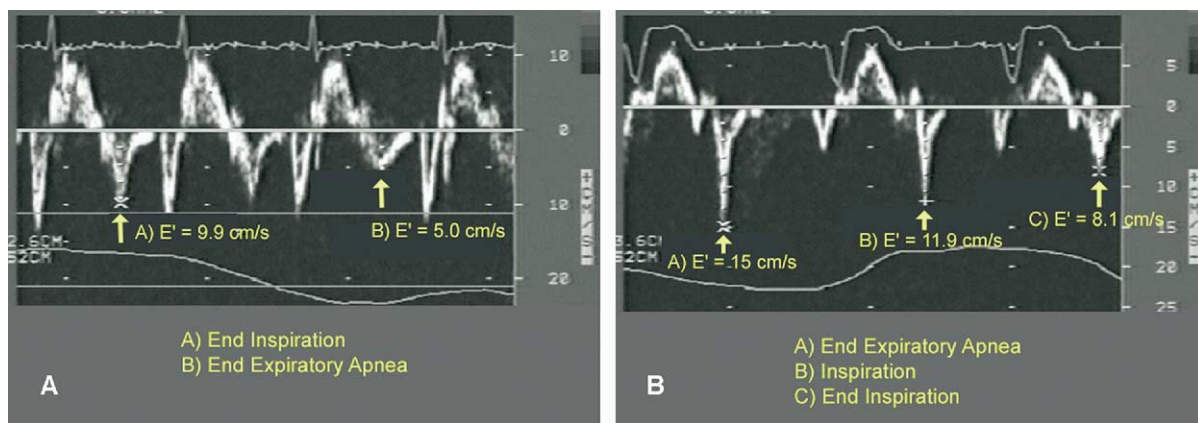


Figure 6 **A**, Effects of respiration on Doppler tissue imaging velocities measured at lateral mitral annulus. A significant beat-to-beat variation of E' velocity is demonstrated. The E' velocity measures 9.9 cm/s at end inspiration compared with that of end-expiratory apnea, where E' velocity measures 5 cm/s. **B**, Considerable beat-to-beat variation of the peak E' velocities in a healthy young patient during normal respiration. The E' velocity measures 8.1 cm/s at end inspiration, well below the normal range (20 ± 3)²⁶ and likely underestimates the true E' velocity. The annular E' velocity at end-expiratory apnea (15 cm/s) likely represents true annular velocities for this patient.

Table 2 Doppler tissue imaging echocardiographic data obtained at the lateral annulus in 103 healthy participants²⁶

	Age (y)							*P value
	20-29 (n = 11)	30-39 (n = 12)	40-49 (n = 24)	50-59 (n = 13)	60-69 (n = 17)	70-79 (n = 14)	≥80 (n = 12)	
E' (cm/s)	20 ± 3	18 ± 4	16 ± 4	14 ± 3	12 ± 3	11 ± 4	9 ± 2	<.0001
A' (cm/s)	11 ± 1	11 ± 3	12 ± 2	11 ± 3	14 ± 4	16 ± 5	13 ± 3	<.0001
E'/E'	4.0 ± 1.0	5.0 ± 1.0	5.2 ± 1.2	5.7 ± 1.4	6.2 ± 1.8	7.2 ± 3.2	8.0 ± 2.4	<.0001

*Mean values by decade compared using analysis of variance.

greater than 10 were shown in many older healthy individuals.²⁶ Thus, it appears that there is some overlap between healthy control subjects and disease states in the older population.

Reproducibility of DTI

To date, few studies have reported on the reproducibility of annular DTI.^{2,5} Vinereanu et al⁵ showed the best interobserver reproducibility of annular diastolic velocities when obtained from the lateral mitral annulus ($\pm 16\%$ for the E' wave, $\pm 9\%$ for the A' wave). Given the limited data available on reproducibility in DTI, more studies are needed to compare not only DTI velocities by multiple observers, but differences in DTI velocities obtained in the same patient. Also, it would be desirable to know how DTI velocities among ultrasound vendors differ. Moreover, special attention to technical factors along with more accurate Doppler beam alignment perpendicular to the annulus may increase reproducibility (Figure 7).

SYSTEMATIC APPROACH FOR ACQUIRING ACCURATE DTI WAVEFORMS

The Sonographers Checklist for More Accurate and Reproducible DTI

The following is a systematic approach that can guide the sonographer to obtain more accurate and reproducible annular Doppler tissue tracings.

1. Determine if the ultrasound manufacturer has preset Doppler tissue settings.
2. Optimize the apical 4-chamber view by aligning the cursor as parallel as possible through the annulus to avoid possible underestimation of the Doppler signal; an angle of insonation less than 20 degrees parallel to annular plane will allow for more accurate Doppler velocities.
3. Sample volume size should be adjusted proportionally to annular motion: use a sample volume of approximately 3 mm for the septal annulus and 5 mm for lateral annulus. Carefully visualize

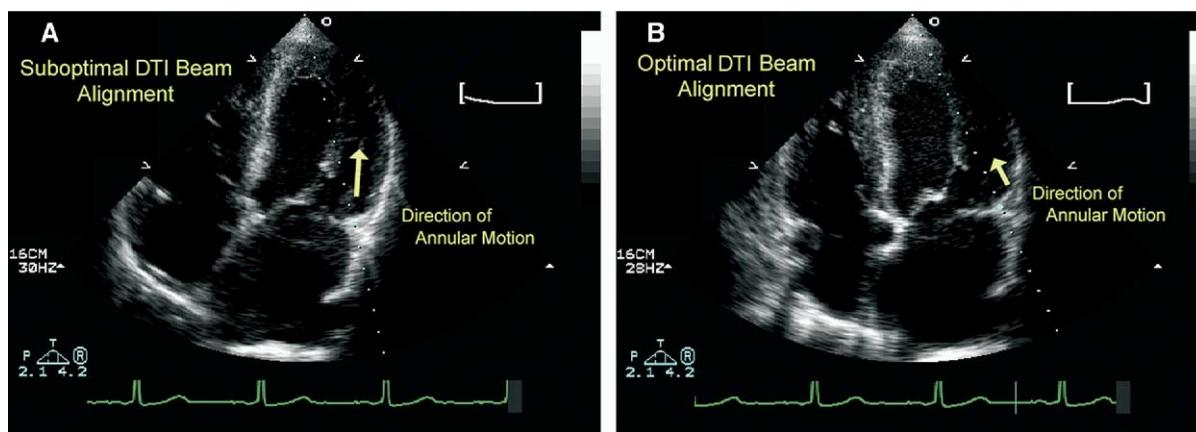


Figure 7 Suboptimal and optimal annular Doppler tissue imaging (DTI) beam alignment. **A**, Large angle of insonation (increased cosine θ) between Doppler beam and lateral annulus. As with other Doppler techniques, large insonation angle (cosine $\theta > 20$ degrees) can lead to significant underestimation of annular velocities. **B**, In same patient, Doppler beam aligned more parallel ($\theta < 20$ degrees) to motion of mitral annulus. Alignment will result in more accurate recordings of annular velocities.

the sample volume relative to annular motion and increase or decrease the sample volume size accordingly.

4. Once the Doppler cursor is aligned optimally, activate the Doppler tissue preset. Decrease the Doppler scale to less than 25 cm/s for better visualization of the peak annular velocities. A sweep speed between 50 and 100 mm/s is adequate for measurement of peak annular velocities.
5. Ask the patient to breathe in, breathe out, and then hold their breath at the end of expiration. Carefully reposition the sample volume directly into the selected portion of the annulus. Activate pulsed wave Doppler tissue. Peak DTI waveform velocities should be uniform, consistent, with little or no beat-to-beat variation of the peak velocities.

Conclusion

This review, technical considerations, and suggested protocols can be used as a guide for the sonographer to comprise more accurate and reproducible Doppler tissue tracings. DTI is useful for estimating filling pressures, which requires a practical and systematic approach. Moreover, DTI can provide important insights into patients' cardiac function.

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