Intraoperative Doppler Tissue Imaging Is a Valuable Addition to Cardiac Anesthesiologists' Armamentarium: A Core Review

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Endocardial motion and surface/volume changes during the cardiac cycle are echocardiographic methods for regional (analysis of wall motion) and global (fractional area change, stroke volume, and ejection fraction) evaluation of cardiac function. These conventional methods can be subjective, and/or time consuming and, depending upon circumstances, may divert the anesthesiologist's attention from intraoperative activities. Doppler tissue imaging (DTI) is a novel echocardiographic technique, which displays and measures systolic and diastolic velocity from a myocardial region. DTI is simple to perform and independent of adequate endocardial imaging. The numeric information (velocity or time intervals) is easily obtained and measured. Assessment of systolic and diastolic function on regional (detection of ischemia) as well as global level (ejection fraction, grading of diastolic dysfunction) and evaluation of filling pressure can be derived from DTI signals and used by any practicing cardiac anesthesiologist. This review describes the principles, imaging modalities, and clinical applications of DTI.
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Intraoperative transesophageal echocardiography (TEE) is commonly used for the evaluation of systolic and diastolic function of the right (RV) and left ventricle (LV) in cardiac or noncardiac surgical cases. A variety of estimations and measurements are performed with two-dimensional (2D) and Doppler echocardiography, using transgastric and mid-esophageal TEE views (Table 1).[1,2] Dependence on clear and crisp visualization of both epi- and endocardium, error in measurements, calculations based on geometric assumptions that may not correspond to the true shape of the cardiac chamber, and examiner's experience level[3] may make such evaluations prone to error. Additionally, these methods cannot distinguish the effect of loading conditions on myocardial function. Doppler tissue imaging (DTI) is a novel ultrasound tool less frequently used by anesthesiologists which measures regional myocardial velocities in systole and diastole, and may be less operator-dependent than 2D or conventional Doppler.[4] DTI is easy to perform and comprehend and provides objective information that can be readily used intraoperatively. (Table 2) This overview will include a description of the principles and practical aspects regarding acquisition and measurement of myocardial velocities, as well as the intraoperative clinical applications of DTI measurements.

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Principles of DTI

The interaction of ultrasound with a moving target produces a reflected signal which has a different frequency than the transmitted ultrasound wave. Based on this Doppler effect, spectral (pulsed or continuous wave) and color flow Doppler is used in clinical practice to study blood flow using the equation

$$velocity = (\Delta f \times c)/(2f_o \times cos\theta)$$

where Δf is the frequency difference, c is the speed of sound in biological tissues (1540 cm/s), f_o is the frequency of the transmitted ultrasound wave, and $\cos\theta$ is the cosine of the angle of incidence between the ultrasound plane and the direction of blood flow. Similar frequency changes occur when ultrasound is reflected off the moving myocardium. Myocardial Doppler signals have lower velocity (in the range of −20 to +20 cm/s) and higher amplitude, when compared to blood flow. DTI modifies the processing of the returned Doppler signal, thus enabling recording and displaying of Doppler signals produced by any

Table 1. Conventional Echocardiographic Techniques for Evaluation of Cardiac Function

	Echocardiographic		Information	
Measurement	View	Mode	Qualitative	Quantitative
Dimensions				
Diameter End-diastolic End-systolic	TG mid SAX	2D ± M-mode	√	√
Wall thickness	TG mid SAX	2D ± M-mode (need to image endo- and epicardium)		√
LV global systolic function				
% Fractional Shortening	TG mid SAX	2D	√	√
% Fractional Area Change	TG mid SAX	2D	√	√
Stroke volume % ejection fraction	ME 4C and 2C	2D (method of discs or area-plane method)	√	√
Stroke volume	Deep TG and TG LAX	2D (measurement of LVOT diameter) Doppler (LVOT VTI)		√
+dP/dt	ME 4C or LAX	Doppler (requires presence of MR jet)		√
LV regional systolic function				
Wall motion	ME 4C, 2C and LAX, TG mid SAX and 2C	2D	√	
LV global diastolic function				
Transmitral flow pattern	ME 4C and LAX	Doppler (patterns influenced by factors other than diastolic properties)	√	
Pulmonary vein flow	ME 4C and LAX	Doppler (patterns influenced by factors other than diastolic properties)	√	
RV global systolic function				
	ME 4C TG MID SAX	2D	√	

2D = two-dimensional; C = chamber; ME = mid-esophageal; MR = mitral regurgitation; LAX = long axis; LVOT = left ventricular outflow tract; SAX = short axis; TG = transgastric; VTI = velocity time integral; +dP/dt = first derivative of positive pressure change.

Table 2. Intraoperative Applications of Doppler Tissue Imaging (DTI)

Left ventricle
Regional systolic function: detection of ischemia
Global systolic function: estimation of ejection fraction
Diastolic function: classification of diastolic pattern
Estimation of filling pressure
Valvular disease
Detection of subclinical ventricular dysfunction
Cardiomyopathy
Differentiation between restrictive cardiomyopathy and constrictive pericarditis
Prognosis in systolic heart failure
Right ventricle
Global systolic function: calculation of ejection fraction

myocardial segment.[5] An example of conventional Doppler and DTI is shown in Figure 1.

Display Formats of Doppler Tissue Imaging

Newer, high-end echocardiographic systems, such as Sequoia 256 or 512 (Siemens/Acuson, Mountain View, CA), Sonos 7500 (Philips, Bothell, WA), Vivid7 (GE/Vingmed, Horten, Norway), are capable of obtaining and measuring myocardial velocities with sufficient accuracy for clinical purposes.[6,7]

Color DTI is obtained in the same manner as conventional color flow Doppler. A color DTI sector is positioned over the myocardial wall of interest and *mean* velocities are computed using autocorrelation analysis. Myocardial velocities are displayed in blue color if directed away from the transducer and in red if directed toward it. The color myocardial velocities are superimposed on a gray scale, 2D tomographic image (mid-esophageal or transgastric views).[8] (Videos 1 and 2) (Please see video clip available at www.anesthesia-analgesia.org) (Fig. 2A,B) In this way, only qualitative information (no numerical value of myocardial velocity) with high spatial, but low temporal, resolution is provided.[9] This is the reason why 2D color DTI has limited intraoperative applications. Newer systems allow off-line processing of a color DTI cine loop by adding an M-mode cursor (Fig. 2C,D) or by placing one or more sample volumes (Fig. 3B) to display regional myocardial velocities in spectral format (see below).

Spectral DTI measures and displays *peak* myocardial velocity with pulsed wave Doppler from within a sample volume placed in the desired myocardial region. This is done in the same manner as when blood flow velocities are recorded with conventional pulsed wave Doppler (Fig. 3). Myocardial velocities are displayed below or above the zero-velocity baseline if directed away from or toward the transducer, respectively. Timed to the electrocardiogram signal, the DTI spectral display is comprised of a systolic velocity (S′) and two opposite directed velocities, in early diastole (E′) and after atrial contraction (A′).[5] In the absence of disease, E′ precedes entry of blood in the LV, and appears earlier than the transmitral early

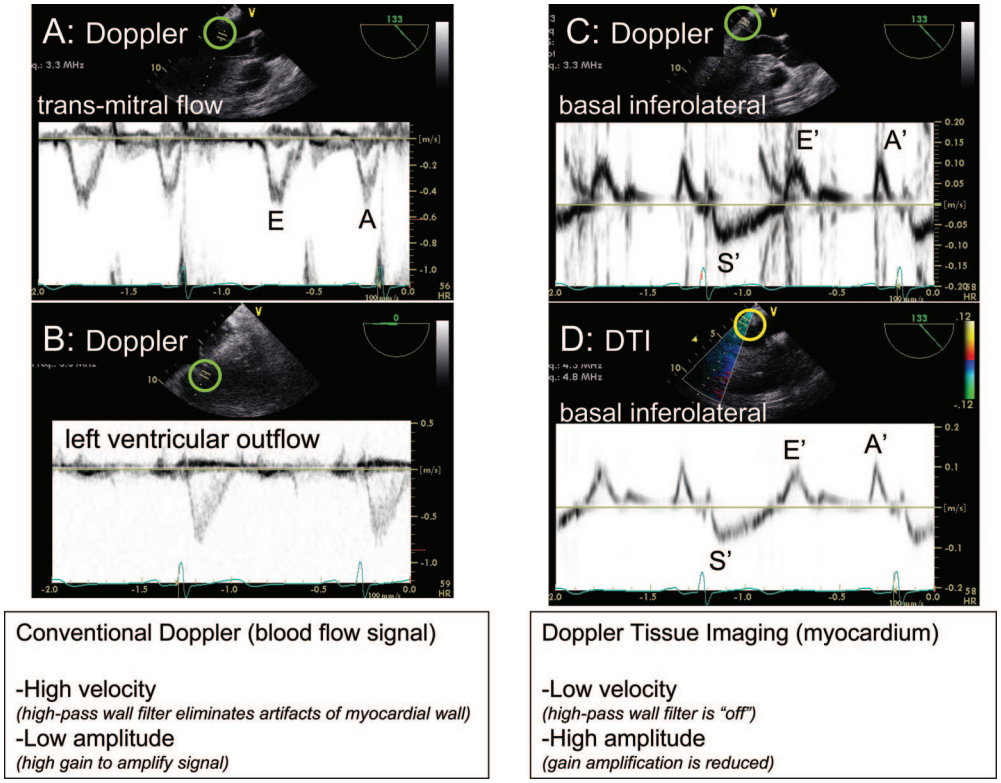


Figure 1. Doppler interrogation of blood flow and myocardial motion. (A,B) Doppler of blood flow. The pulsed wave sample volume is placed between the tips of mitral leaflets (A, mid-esophageal long axis view) and just below the aortic valve in the left ventricular outflow tract (B, deep transgastric view). (C) Doppler of myocardial motion. The conventional pulsed wave Doppler sample volume is placed at the basal inferolateral left ventricular segment (mid-esophageal long axis view). The typical spectrum of myocardial velocity has a systolic (S'), early (E'), and late (A') diastolic waves. Myocardial signals have lower velocity (compare scale in C vs A and B; scale is in m/s) and higher amplitude (the velocity envelope in C is "thick," despite minimal gain). (D) Engaging the preset Doppler tissue imaging (DTI) function displays myocardial velocities without adjustment of Doppler signal (sampling is from same area and patient). Notice clarity of spectral display (scale is same as in C). The myocardial diastolic velocities (E' an A') are in opposite direction to transmitral flow. A = late transmitral flow velocity; E = early transmitral flow velocity.

(E) blood flow velocity.[10] In the mid-esophageal views, DTI diastolic velocities are a mirror image of the transmitral blood flow because the myocardium moves in an opposite direction to blood flow, i.e., the cardiac base moves away from the apex as blood flows forward through the mitral annulus and toward the apex during systolic ejection (Fig. 1, compare A vs D).[11] If the signal is of adequate quality, biphasic signals of low velocity are displayed during isovolumic contraction (between A' and S') and isovolumic relaxation (between S' and E') (Fig. 3A). These low velocity and short duration waves are most likely related to local shape changes as well as cardiac rotation and torsion.[12] DTI velocities are also described with the subscript "a" (for annular) if recorded from the mitral annulus, or with the subscript "m" (for myocardial) if recorded anywhere in the myocardium. Practically, the DTI velocities from the basal LV segments are the same as those recorded next to the mitral annulus (Fig. 3B), unless there is extensive calcification of the mitral annulus.[13] In this review, S', E', and A' refer to DTI velocities recorded next to the mitral annulus, and represent longitudinal cardiac motion. The differences between the DTI display formats are summarized in Figure 4.

Techniques for Recording DTI

Longitudinal velocities are recorded in the mid-esophageal views (Fig. 5). Transverse velocities are recorded in the transgastric mid-short axis view (Fig. 6). However, excessive cardiac motion in the transverse axis can make recording of transverse spectral DTI myocardial velocities cumbersome and error-prone, and thus is not usually performed intraoperatively. Most current echocardiographic systems are equipped with a preset function that enables DTI (VTI, Velocity Tissue Imaging in GE/Vingmed; PW-TDI, pulsed-wave Tissue Doppler Imaging in Siemens/Acuson and Philips).

The technique for recording spectral DTI velocities is described in Table 3, Figure 7 and Videos 3 and 4).[14] (Web Supplement Fig. 1 for a Siemens/Acuson system.) Measurements can be performed right away or the DTI loop is saved in digital format for off-line analysis.

DTI Myocardial Velocities, Myocardial Function, and Limitations of DTI

Myocardial velocities, recorded with DTI from the basal segments next to the mitral annulus, allow quantification of regional longitudinal cardiac motion in a manner not previously possible. From a clinical

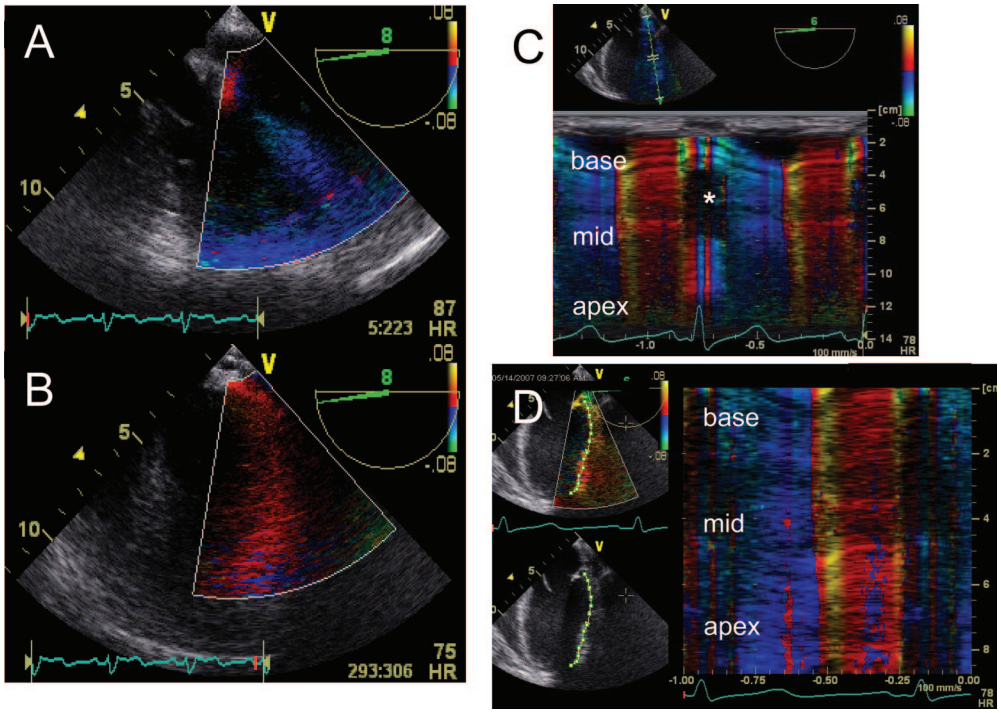


Figure 2. Color Doppler tissue imaging (DTI) of the left ventricle (LV) in the mid-esophageal four chamber view. (A) Color DTI of inferoseptal wall (shown during beginning of systole and colored blue). (B) Color DTI of anterolateral wall (shown during end of diastole and colored red). The velocity scale, shown at top right (Nyquist limit ±8 cm/s), is lower than in conventional color Doppler (usually ±60 cm/s). (C) Addition of M-mode cursor on color DTI of the anterolateral LV wall displays velocities from base (top) to apex (bottom). Notice absence of velocities (asterisk) due to wall movement out of color DTI sector. (D) Drawing an anatomic ("virtual") M-mode cursor on the anterolateral LV wall color DTI will display myocardial velocities from basal to apical segments. This is an off-line (postprocessing) function, not available in all echocardiographic systems.

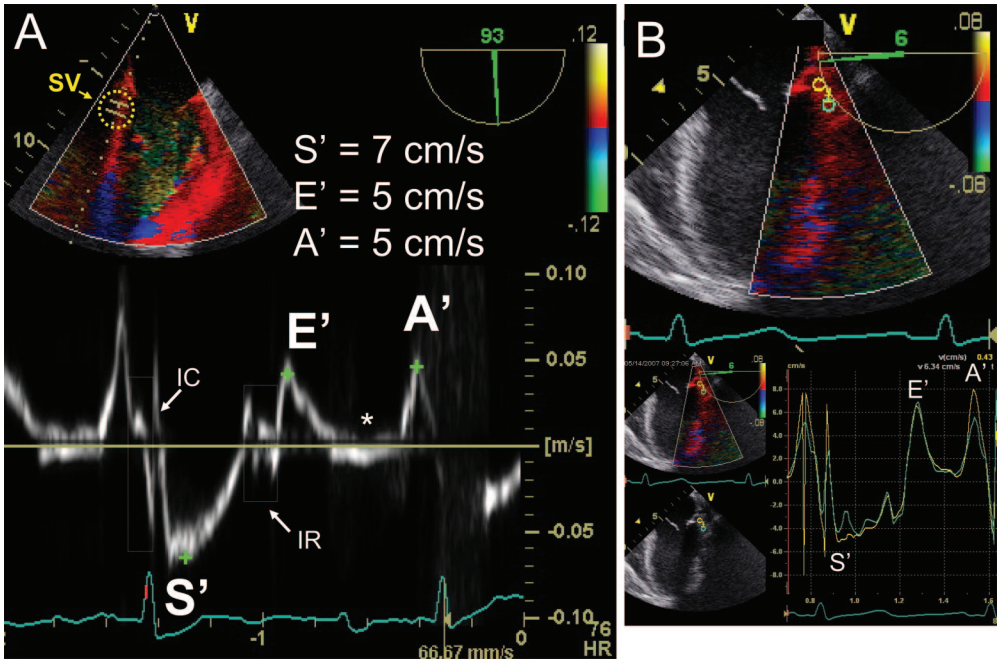
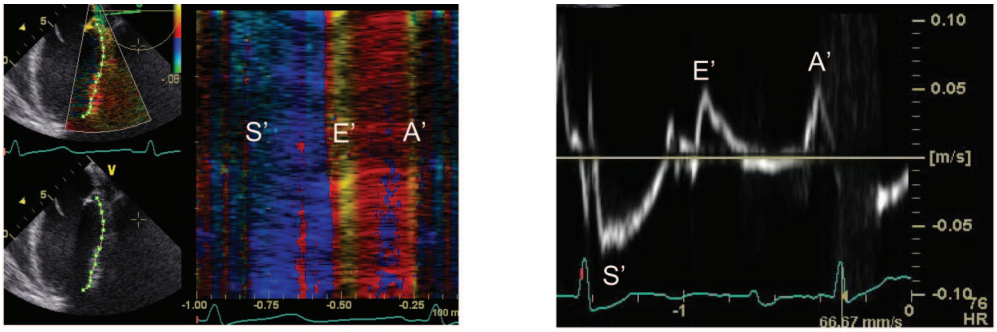


Figure 3. Spectral Doppler tissue imaging (DTI) of the left ventricular basal inferior segment (mid-esophageal two chamber view). (A) After application of color DTI (Nyquist limit set at ±12 cm/s), a sample volume (SV) is placed in the basal inferior segment, next to the mitral annulus. Activation of the pulsed wave DTI preset mode produces a spectral display of myocardial velocities. Peak velocity (+) is measured from the outer border of the modal display (periphery of spectral signal). S′ wave is in opposite direction to diastolic waves, as myocardium changes direction of motion between systole and diastole. No velocity is recorded during diastasis (asterisk). During isovolumic contraction (IC) the initial DTI wave is in opposite direction to A′ and the second wave opposite to S′. During isovolumic relaxation (IR) the initial DTI wave is opposite to S′ and the second wave opposite to E′. (B) Spectral DTI from off-line (postprocessing) placement of a SV in a digitally saved color DTI loop (top). Velocities lateral to mitral annulus (yellow) and of basal myocardium (green) are identical (bottom).



Color DTI (+ M-mode)		Spectral DTI
"live": 2D or M-mode "off-line": anatomic M-mode	***Acquisition***	"live"
Mean (qualitative)	***Velocity displayed***	Peak (quantitative)
2D: poor + M-mode: very good	***Temporal resolution***	Better than color 2D
Very good: analysis of all segments is feasible	***Spatial resolution***	Poor: unable to differentiate endo- from epicardial velocities
Entire wall	***Segments analyzed***	Part of segment
Required for off-line analysis of velocities	***Digital storage***	Not required

Figure 4. Color and spectral Doppler Tissue Imaging (DTI) display formats (top) and comparison of color and spectral DTI (bottom).

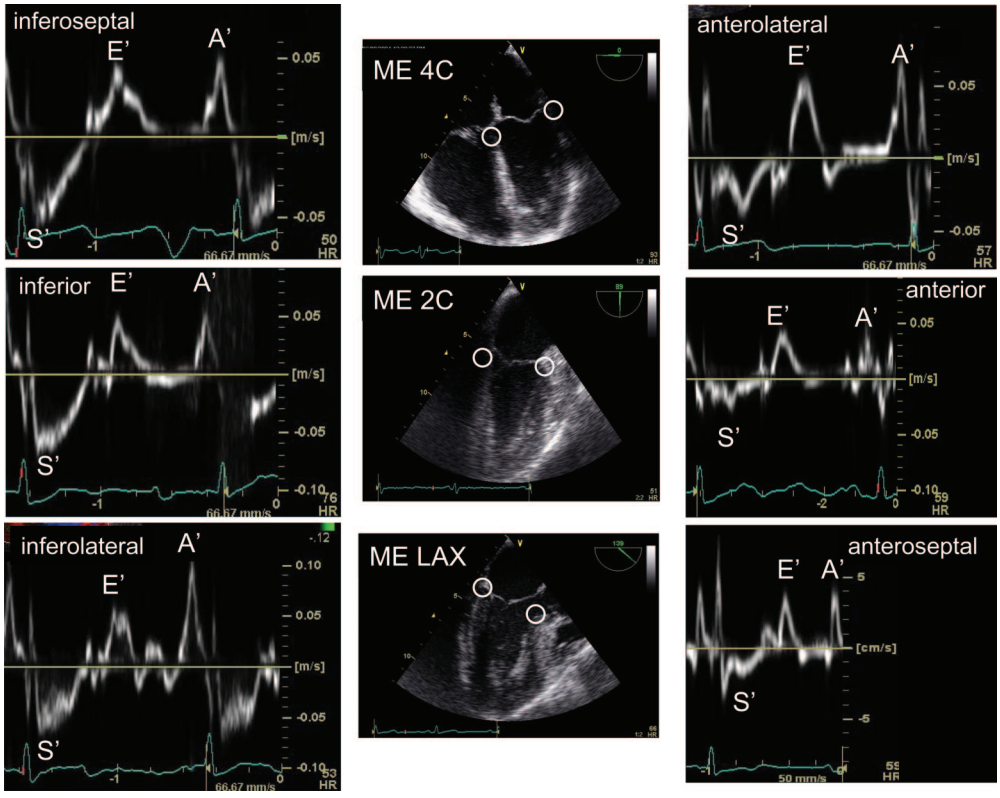


Figure 5. Longitudinal myocardial velocities (spectral Doppler tissue imaging) recorded from sample volumes (white circles) positioned lateral to the mitral annulus, in the standard SCA/ASE tomographic views of the left ventricle: mid-esophageal (ME) four chamber (ME 4C), two chamber (ME 2C), and long axis (ME LAX). Notice the relative blunting of S′ velocities in anterior and anteroseptal myocardial segments, where Doppler angle between the direction of ultrasound and the plane of motion is usually >20°. S′ = systolic; E′ = early diastolic; A′ = late diastolic myocardial velocities.

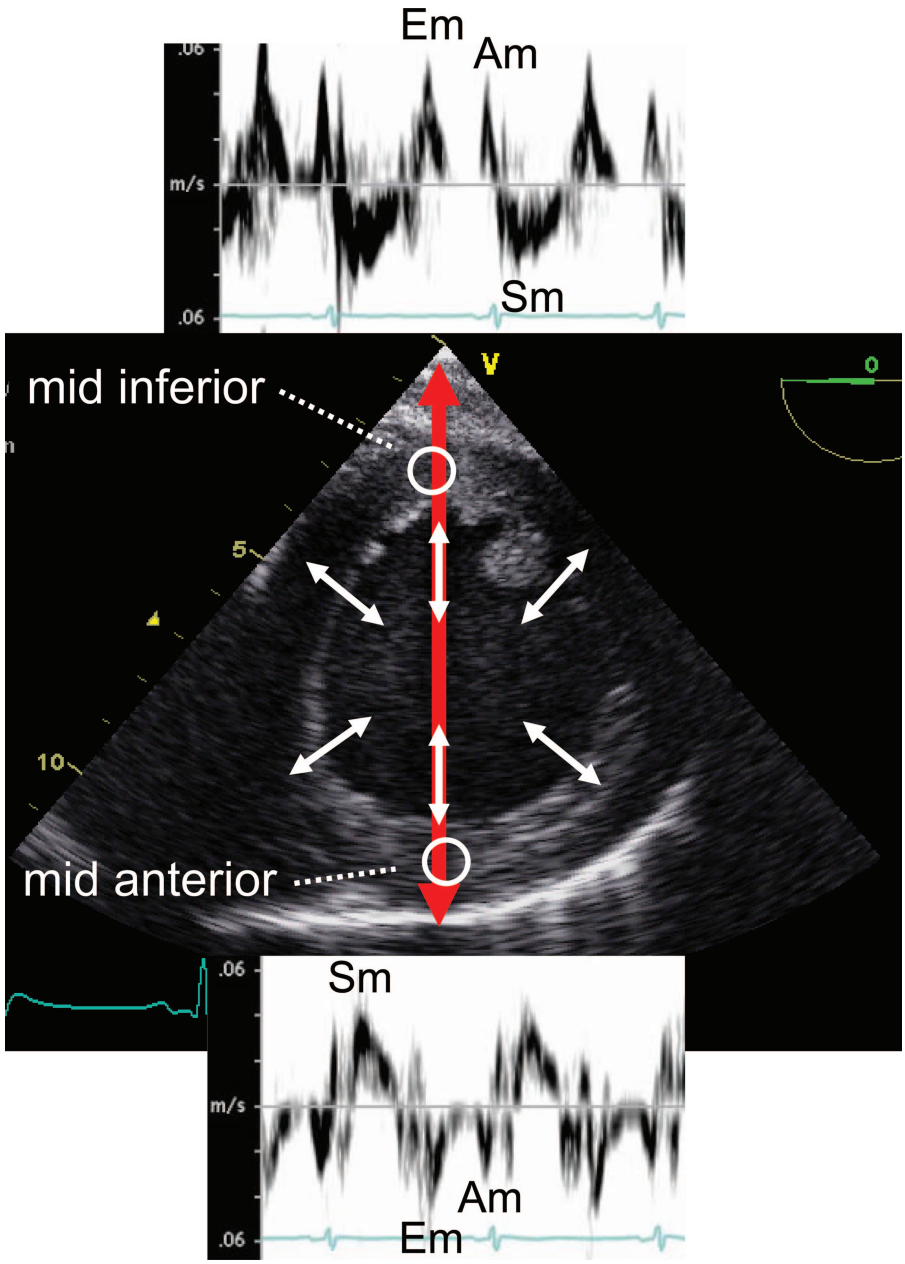


Figure 6. Transverse myocardial velocities (spectral Doppler tissue imaging [DTI]) recorded from sample volumes (white circles) positioned in the center of the left ventricular mid inferior (top) and anterior (bottom) segments (transgastric mid short axis view). The segmental motion during systolic thickening and diastolic thinning is in opposite direction, hence the mirror image of velocities. DTI from the septal and lateral segments is not possible because of increased angle between Doppler (red arrow) and direction of wall motion (arrows). Sm = systolic myocardial velocity; Em = early diastolic myocardial velocity; Am = late diastolic myocardial velocity.

point of view, such recordings of the longitudinal cardiac motion provide important data about subendocardial function, the region most vulnerable to ischemia.[15]

The appreciation of clinical applications and limitations of DTI requires comprehension of myocardial anatomy. Myocytes are organized in sheets that lie in planes parallel to the cardiac long axis. Myocyte orientation varies within these planes: it is circumferential in the mid-wall and longitudinal in the endocardial region (forming a right-handed helix) and epicardial surface (forming a left-handed helix).[16] During systole, the endo- and epicardial myocyte sheets take a more perpendicular angle toward the mid-wall. As a result, a 14% shortening of the long axis is accompanied by a 40% thickening of the LV wall in the radial axis.[17] (Fig. 8) This is seen with TEE in the mid-esophageal views as systolic descent and diastolic ascent of the mitral annulus, and in the transgastric views as systolic thickening and diastolic thinning of the LV wall segments.

The limitations of DTI are related to Doppler. DTI measures only the component of motion which is parallel to the ultrasound beam, and DTI velocities decrease by about 20% if the Doppler angle is approximately 30°.[18] In addition, the immobile spectral DTI sample volume records velocity produced by both longitudinal and transverse cardiac motion. This complex motion cannot be further analyzed with DTI because of poor spatial resolution. In order to optimize Doppler measurements, it is important to note that, i) in the mid-esophageal views, the mid and apical segments have an inward curvature as the broad LV base tapers towards the apex, and ii) in the transgastric views, the septal and lateral segments are curved. Therefore, ideal "matching" between the

Table 3. Acquisition of Myocardial Velocities with Doppler Tissue Imaging (DTI)

Mode	Step	Action	Comment
2D	1	Narrow sector image and adjust depth over desired segment (usually mitral annulus in ME 4C, 2C or LAX views)	Maximizes frame rate
Color DTI	2	Activate preset DTI function	Displays myocardial Doppler shift in color
	3	Place a narrow DTI sector over area of interest	Increases temporal resolution
	4	Select appropriate velocity	Use Nyquist scale ±15 cm/s
	5	Adjust 2D and color DTI gains	Only tissue is "colorized" Enables better identification of tissue boundaries for positioning of DTI sample volume
	6	Manipulate TEE probe to minimize Doppler angle	Tissue motion and ultrasound propagation should be as parallel as possible
	7	Store color DTI clip in digital format	For post-processing application of conventional or anatomic M-mode or for extraction of mean velocities with off-line positioning of DTI sample volume
	8	Activate cursor, position and adjust size of sample volume (3–5 mm)	Only velocities from within the sample volume are displayed
Spectral DTI	9	Activate pulsed wave Doppler	Spectral display of peak tissue velocities
	10	Adjust	
		Velocity range (±20 cm/s)	Myocardial velocities are slower
		Doppler gain	Narrows envelope ("thickness") of modal velocity, increases accuracy of measurement
		Decrease low velocity reject	Improves detection of onset and end of velocity
		Sweep speed 50–100 mm/s	Increases temporal detail of velocity spectrum
	11	Store in digital format	Off-line velocity and time interval measurements

2D = two-dimensional; ME = mid-esophageal; 2C = two chamber; 4C = four chamber; LAX = long axis.

Doppler beam and the direction of myocardial motion occurs (a) in the basal segments in the mid-esophageal views and (b) in the middle of the inferior and the anterior segment in the transgastric views. If these prerequisites are met, DTI recordings will approximate the motion of longitudinal and circumferential fibers, respectively.

Factors Affecting DTI Velocities

1. Myocardial DTI velocities are directly related to the number of contracting myocytes and myocardial β-adrenergic receptors density.[19] Normal myocardial segments have higher S′ and E′ and myocardial β-adrenergic receptor density and lower amount of interstitial fibrosis when compared with dysfunctional segments.[19]
2. Location: more fibers are found towards the LV base than apex and in lateral and inferior than septal segments.[20] This results to heterogeneity: DTI velocities are lowest in the septum, and all velocities decrease from the basal to the mid-apical segments (Fig. 9).[21–24] Therefore, velocities from different walls (i.e., septal and lateral in the mid-esophageal four chamber view) or segments cannot be used interchangeably.
3. Heart rate: S′ velocity is positively correlated with heart rate.[25] Activation of the sympathetic nervous system increases both heart rate and contractility (and thus, mitral annular excursion and S′).[25]
4. Age: advancing age increases A′ and decreases S′ and E′ velocities[25–29] as fibrous tissue replaces myocardial fibers.
5. Preload: S′ and E′ velocities are directly dependent on preload,[30,31] if cardiac function is normal. The effect of preload on A′ is less pronounced. In diastolic dysfunction, E′ becomes relatively preload-independent and remains low even if the LV filling pressures are increased.[32]
6. Afterload: In healthy subjects, acute increases in afterload decrease E′ velocity,[33] whereas in patients with chronically increased afterload, both S′ and E′ are decreased.[34]
7. Tethering: DTI velocities are recorded from an immobile sample volume, and presence of a DTI velocity cannot exclude passive motion of the segment due to tethering to adjacent segments. This may account for conflicting results regarding the effect of load alterations on basal versus other myocardial segments.[30]

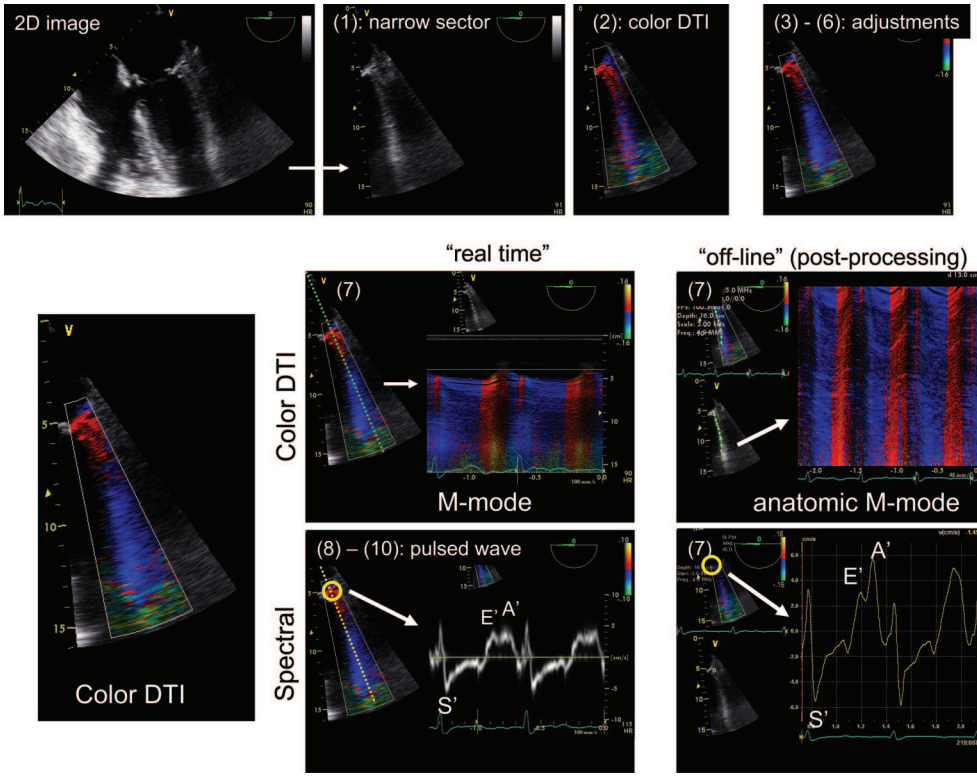


Figure 7. Acquisition of myocardial velocities with Doppler tissue imaging (DTI). A two dimensional (2D) image (mid-esophageal four chamber view) is acquired and the sector image is narrowed (1). Color DTI preset is activated (2) and adjusted (3–6). Myocardial velocities can be displayed with color DTI, color DTI with M-mode (7) or spectral (from a sample volume) format (8–10). Numbers in parentheses correlate with "steps" in Table 3.

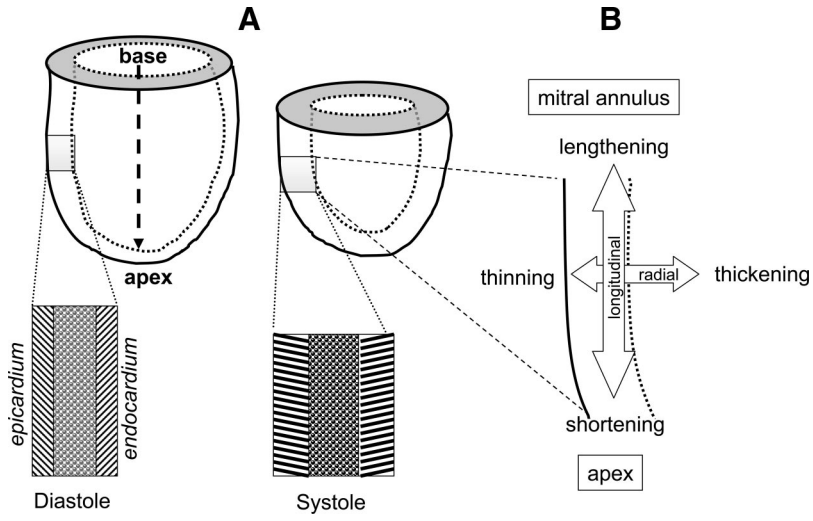


Figure 8. Functional anatomy of the left ventricle (LV) in a transesophageal echocardiography mid-esophageal view. (A), top: The LV base descends towards the relatively immobile apex during systole and ascends during diastole. (A), bottom: Myocardial fibers lie in planes parallel to LV long axis. Within the endocardial and epicardial planes, fibers form a right-handed and a left-handed helix respectively. In the mid-wall, the fibers are oriented circumferentially. (B) Axes and terminology of cardiac motion relative to mitral annulus and apex.

8. Pericardiotomy and mechanical ventilation: although theoretically both may affect DTI recordings because of cardiac motion (e.g., during cardiac surgery and opening of the pericardium), this has not been observed[35]* intraoperatively. The effect of respiration can be further minimized if DTI is used to record longitudinal velocities during end-expiration.

The clinical implications of the above is that S′ should not be used as a substitute for contractility[36] and that underlying hemodynamics should be considered when repeated measurements are performed at different times. However, repeated DTI measurements from a single site may reveal the effect of various loading conditions on LV wall motion dynamics. This was seen

*Skubas N, Ryjikov N, Slepian R, Levin S, Girardi L, Krieger K, Tunick PA, Kronzon I. The effect of pericardiotomy on left ventricular diastolic myocardial tissue velocity. J Am Soc Echocardiogr 2004;17:PI-44 (abstract).

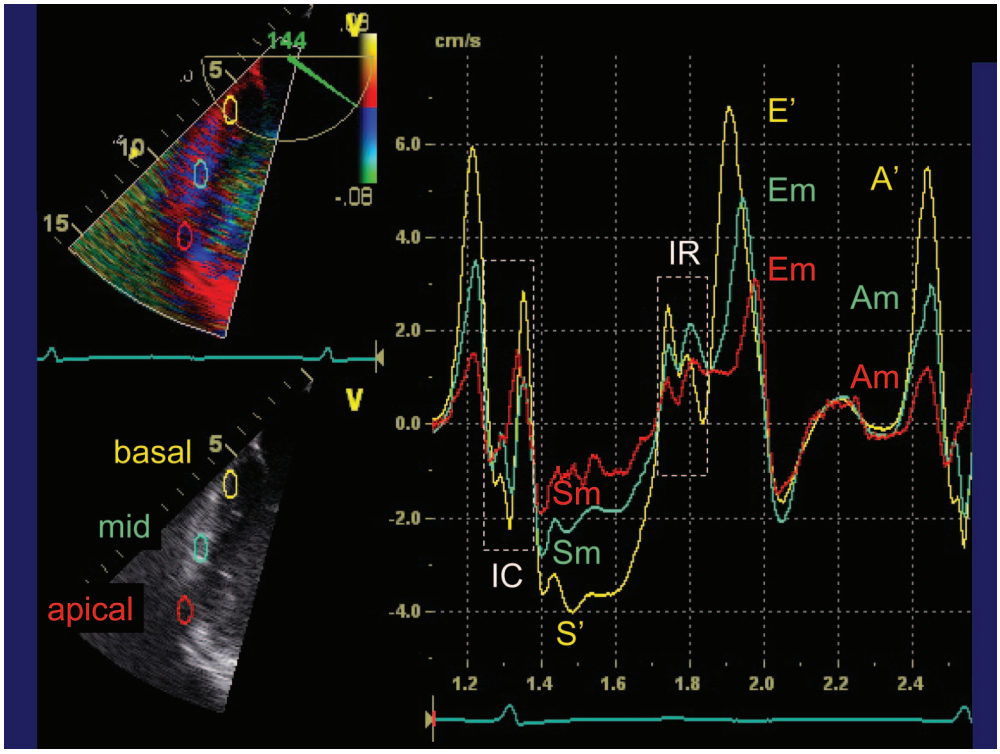


Figure 9. Heterogeneity of myocardial velocities. Spectral display of myocardial velocities with postprocessing of color Doppler Tissue Imaging (DTI). Sample volumes are placed in basal (yellow), mid (green), and apical (red) myocardial segments of the inferolateral left ventricular wall (mid-esophageal long axis view). Spectral velocities are shown on the right. For all velocities (systolic [S′ and Sm], early diastolic [E′ and Em] and late diastolic [A′ and Am]), there is a declining gradient from base to apex (scale is −5 to +7 cm/s). IC = isovolumic contraction; IR = isovolumic relaxation.

in mechanically ventilated, postcoronary revascularization patients when administration of 500 mL colloid IV, caused a significant increase in S′ (8.4 ± 2.6 – 9.6 ± 2.5 cm/s, $P < 0.001$).[31] It would also be prudent to regard the mitral annulus or basal myocardial velocity as reflecting the velocity of the entire wall (basal, mid, and apical segments).

DTI Measurements

Possible measurements using DTI include peak velocity (cm/s), acceleration or deceleration (cm/s^2) and time intervals (ms). From the clinician's point of view, peak velocity and the E′/A′ ratio provide the most information. DTI velocities are generally lower when recorded with TEE than with transthoracic echocardiography (TTE).[37] In TTE, the different acoustic windows used place the basal segments in the far field and allow for more parallel alignment with the Doppler beam. Even under controlled, experimental conditions,[38] DTI recordings between TTE and TEE are not comparable. Few studies have reported DTI in anesthetized, mechanically ventilated patients (Table 4).[31,35,37,39–41]†

Normal DTI values recorded with TTE are shown in Table 5.[5,42] Postbypass, DTI velocities change, probably reflecting the effects of cardiopulmonary bypass or vasoactive medications.[37,40,41]

†Brown NI, Slepian R, Purcell MH, Mishra R, Skubas N. Atrial contraction is influenced by ventricular systole: a tissue Doppler echocardiographic study in cardiac surgical patients. American Society of Anesthesiologists Annual Meeting, Atlanta, GA 2005;A-346 (abstract).

Clinical Applications of DTI

The clinical applications of DTI in the nonsurgical patient have been extensively studied. Data of clinical interest to the anesthesiologist or intensive care physician are summarized in Table 6.

Ventricular Contractility

DTI velocities can detect alterations in regional and global LV contractility that compare favorably with sonomicrometry and pressure-volume measurements.[43] The clinical utility of S′ to track changes in LV systolic function was demonstrated in a rapid pacing-induced heart failure model, where S′ was closely related to LV ejection fraction (EF) at all levels of function.[44] Longitudinal S′ correlates better than EF[45] with LV +dP/dt in healthy and diseased subjects without regional wall motion abnormalities (RWMA).[46]

Estimation of Ejection Fraction

S′ velocity is a quick and easy means of estimating LV EF. TTE S′ measurements from a single,[47] or average S′ from two or more, usually opposite, basal segments have been found to correlate well with LV EF.[48–51] Cutoff values or calculation formulae are shown in Table 7.[49,50] If RWMA are present, the estimation or calculation of LV EF should be done using the average S′ of as many segments as possible.[48] The association between S′ and clinical performance has not been extensively evaluated in patients

Table 4. Doppler Tissue Imaging (DTI) Measurements in Anesthetized, Mechanically Ventilated Patients

Author, population	TEE imaging plane/ measurement site	DTI mode	DTI measurement
Norrild[39] Aortic stenosis ± CAD (n = 12)	TG mid SAX: anterior segment	Color DTI (off line spectral)	S′ 3.7 ± 0.7 cm/s
Ama[31] post CABG (n = 42)	ME 4C: anterolateral mitral annulus	spectral	S′: 7.3–8.4 cm/s
Simmons[35] pre-CABG (n = 22)	ME 4C, 2C: basal septum TG mid SAX: anterior	Color DTI (off-line spectral)	S′: −3.6 ± 0.7 cm/s E′: 3.8 ± 0.8 cm/s S′: 4.0 ± 1.4 cm/s E′: −4.5 ± 1.7 cm/s
Brown/ASA 2005 CABG (n = 23)	ME 4C, 2C, LAX: lateral mitral annulus	spectral	S′: −6.7 ± 2.0 cm/s (pre) −5.7 ± 2.1 cm/s (post) A′: 5.7 ± 2.1 cm/s (pre) 7.7 ± 2.4 cm/s (post) E′/A′: 1.2 ± 0.5% (pre) 0.8% ± 0.3% (post)
Williams[37] CABG (n = 20)	ME: basal segments	Color DTI (off-line spectral)	S′-anterior: −3.4 ± 1.7 cm/s (pre) −4.4 ± 2.1 cm/s (post) S′-lateral: −4.4 ± 2.0 cm/s (pre) −5.5 ± 2.1 cm/s (post) S′-posterior: −2.6 ± 1.0 cm/s (pre) −3.4 ± 1.4 cm/s (post) S′-inferior: −5.3 ± 2.3 cm/s (pre) −6.6 ± 3.9 cm/s (post) S′-septal: −4.5 ± 2.9 cm/s (pre) −5.5 ± 2.5 cm/s (post)
Casthely[41] pre CABG (n = 32)	TG mid SAX ME 4C	spectral	E′ 1.3 cm/s S′ 7–8 cm/s E′ 7.5–8.0 cm/s A′ 12.5–13.1 cm/s
Skarvan[40] CABG (n = 42)	TG mid SAX: anterior	spectral	S′: 4.2 [4.0–4.7] cm/s (pre) 5.7 [4.8–6.3] cm/s (post) A′: −3.5 [3.2–3.9] cm/s (pre) −6.0 [5.1–6.9] cm/s (post) E′/A′: 1.5 [1.2–1.7]% (pre) 1.0 [0.8–1.2]% (post)

A′ = late diastolic DTI velocity; CABG = coronary artery bypass surgery; E′ = early diastolic DTI velocity; ME = mid-esophageal; S′ = systolic DTI velocity; SAX = short axis; TG = transgastric; LAX = long axis.

Table 5. Doppler Tissue Imaging (DTI) Velocities: Normal Values Recorded with Transthoracic Echocardiography

Measured with spectral DTI in basal segments				
	Lateral	Septal	Anterior	Inferior
S′ (cm/s)	10.6 ± 2.3	9.9 ± 1.7	9.2 ± 1.8	10.4 ± 2.5
E′ (cm/s)	13.3 ± 3.3	11.5 ± 2.6	11.7 ± 3.4	14.3 ± 3.6
A′ (cm/s)	11.3 ± 2.9	9.5 ± 2.4	10.3 ± 2.9	11.6 ± 2.6
E′/A′	1.5 ± 0.6	1.0 ± 0.7	1.2 ± 0.7	1.3 ± 0.7

Measured with postprocessing of a color DTI	
Mean velocity (±1 SD), factoring in curvature, level and age	
S′ (±1.9) cm/s	6.1 + (1.5 × Level) − (0.06 × Age)
E′ (±2.5) cm/s	10.5 + (1.0 × Curvature) + (2.2 × Level) − (0.39 × Curvature × Level) − (0.12 × Age)
A′ (±1.7) cm/s	0.66 + (1.65 × Curvature) + (1.1 × Level) + (0.5 × Curvature × Level) + (0.04 × Age)

Curvature	Level
1 for straighter septal and inferior walls	0 for apical
0 for more curved lateral and anterior walls	1 for mid
	2 for basal

Values are mean ± 1 SD.

Table 6. Intraoperative Applications of Doppler Tissue Imaging (DTI)

Left ventricle	
Global function	S′ 4.0–4.7 cm/s (prebypass, CI 1.9–2.3 $L \cdot min^{-1} \cdot m^{-2}$)
	S′ 4.8–6.3 cm/s (postbypass, CI 2.3–2.6 $L \cdot min^{-1} \cdot m^{-2}$)
	S′ recorded from mid anterior (TG mid SAX)
Regional function	S′ increases at 1 $\mu g \cdot kg^{-1} \cdot min^{-1}$ dobutamine infusion
Regional ischemia	reduced S′ velocity in affected segments
	appearance of postsystolic shortening
	inverted E′/A′ ratio (E′/A′ <1)
	ECG-Q-to-E′ onset > ECG-Q-to TMF-E onset
Diastolic function	
Normal	E′ >12.5 cm/s (awake patients)
	E′ is preload dependent
	E′/A′ >1
Abnormal	E′ decreases at an early age, even with normal TMF
	E′ <10 cm/s (40–50 yr), E′ <8 cm/s (50–60 yr)
	E′/A′ <1, remains low irrespective of TMF
	(E′/A′ does not pseudonormalize)
Filling pressure	Mean LAP = 2 + (1.3 × E/E′)
	E/E′ <8: low LAP
	E/E′ >15: elevated LAP
Valvular disease	
Mitral regurgitation aortic regurgitation	Presence of contractile reserve if S′ >9 cm/s
Prognosis in heart failure	
Poor prognosis	S′ <3 cm/s
	E′ <3 cm/s
	A′ <4 cm/s
	E/E′ >20
Right ventricle	
Global function	normal %EF if S′ >10–11 cm/s
Evaluation of dyssynchrony	
Presence of mechanical dyssynchrony	Septal to lateral delay >65 ms

A′ = late diastolic DTI velocity; E = TMF early diastolic velocity; E′ = early diastolic DTI velocity; EF = ejection fraction; ME = mid-esophageal; LAP = left atrial pressure; S′ = systolic DTI velocity; TMF = transmitral flow; CI = cardiac index.

undergoing a general anesthetic. S′ from the mid-anterior LV segment (transgastric mid-LV short axis using TEE) correlated well with fractional area change before and after coronary artery surgery.[40]

Detection of Ischemia

DTI is a promising tool for the real-time detection and quantification of ischemia-induced regional myocardial dysfunction. DTI of the longitudinal axis is able to detect ischemia-induced changes earlier[52] and more consistently than epicardial electrocardiogram, myocardial lactate extraction or global hemodynamics changes,[53] even in the presence of normal LV EF and unchanged transmitral flow patterns.[54] In an animal model of regional ischemia, S′, E′, and E′/A′ decreased within 5 s of ischemia onset, in proportion to the reduction in regional myocardial blood flow (as quantified with microspheres). These changes correlated closely to the myocardial shortening decline (recorded with sonomicrometry) and appeared in advance of 2D echocardiographic changes (such as reduction of systolic excursion and passive paradoxic motion).[55,56] The reduction of S′ and E′ during ischemia was accompanied by increased isovolumic relaxation velocity, whereas reperfusion was associated with a transient increase of S′ to a value higher than at baseline, followed by a decrease, identifying myocardial stunning[55] (Fig. 10). Consequently, while DTI may be more sensitive than visual evaluation of RWMA in detecting regional ischemia, it is unable to distinguish active ischemia from reperfusion-induced contractile dysfunction. The isovolumic contraction velocity decreases during milder degrees of myocardial ischemia (reduction of coronary artery flow by 50%)[57] and precedes the development of infarction. Because it disappeared in those segments that eventually developed more than 20% infarcted tissue, it remained unchanged in smaller infarcts.[58]

After a first myocardial infarction, S′ is significantly reduced in all basal LV segments, even when 2D echocardiographic function is normal.[59] The infarcted segments demonstrate the largest reduction in velocity, prolongation of the Q-to-peak-S′ time interval and reduction in E′ without A′ changes, resulting in E′/A′ <1.[48,50,60] In myocardial segments remote from ischemia, DTI velocities will remain the same or even decrease, depending upon the presence or absence of functional reserve.[56] Prolongation of intervals or velocities ratios are easy to measure, are not influenced by the Doppler angle of incidence, and offer additional information in identifying ischemic LV segments. A longer Q-to-peak-S′ interval in the ischemic area delays regional relaxation and leads to systolic

Table 7. Estimation of Ejection Fraction (EF) by Doppler Tissue Imaging (DTI) Systolic (S') Velocity Using Trans-Thoracic Echocardiography

Study, population	DTI mode	S′ site	EF
Gulati[51] n = 55, mixed	Color	Average of 6 basal segments	8.2 × S′ + 3
Fukuda[50] n = 71, 45 with MI	Spectral	Average of 6 basal segments	4.1 × S′ + 13.1
		MI site only	5 × S′ + 11.4
Alam[48] n = 78, MI	Spectral	Average of 4 basal segments	5.5 × S′ + 8
Vinereanu[49] n = 51, 38 with MI	Spectral	Average of 2 basal segments	≥50% if S′ ≥8 cm/s

MI = myocardial infarction.

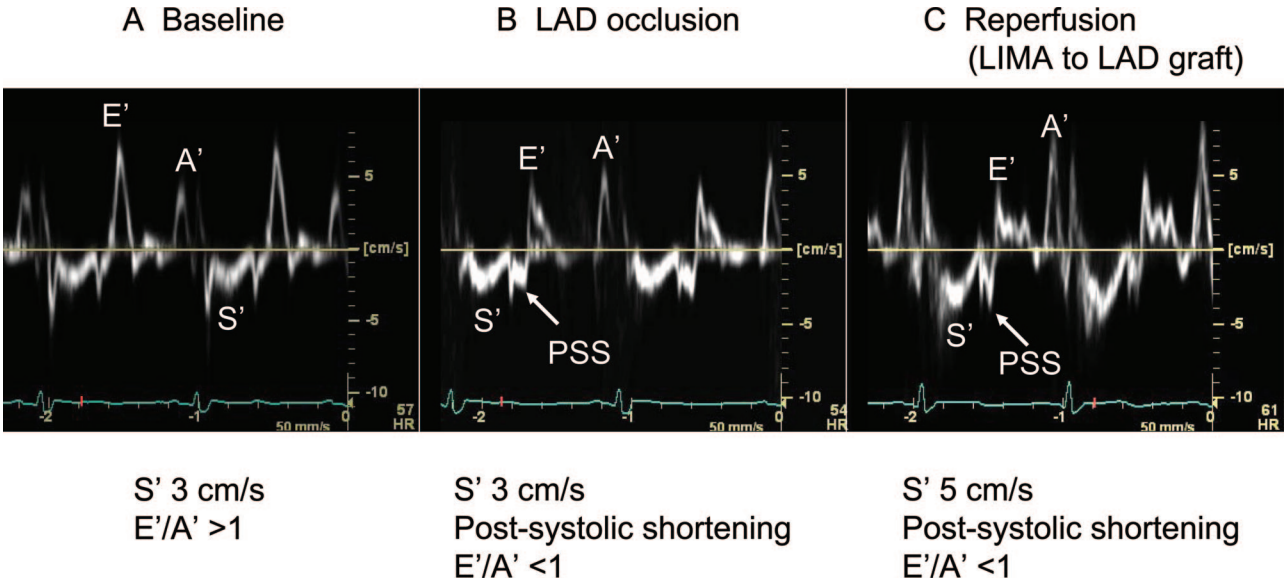


Figure 10. Ischemia detection with spectral Doppler tissue imaging in a patient undergoing off-pump coronary artery bypass surgery. (A) Baseline myocardial velocities. (B) Occlusion of the left anterior descending (LAD) coronary artery caused appearance of postsystolic shortening (PSS) and reversal of E′/A′ ratio. PSS is in the same direction with S′. (C) After reperfusion of the left internal mammary artery (LIMA) to LAD graft, persistence of PSS is characteristic of stunned myocardium. S′ is increased. Recordings were made from basal anterolateral left ventricular wall (mid-esophageal four chamber view). S′ = systolic; E′ = early diastolic; A′ = late diastolic myocardial velocities.

tension persisting in diastole. This manifests as systolic velocity during isovolumic relaxation (appearing in the same direction with S′). This represents postsystolic shortening of the ischemic area[61] (Fig. 10) and is associated with adverse effects on overall systolic and diastolic LV function.[62] Postsystolic shortening is a marker of myocardial viability, as it predicts the recovery of function after coronary reperfusion.[63] An isovolumic relaxation period (S′end-to-E′onset) >85 ms,[64,65] or an earlier onset of transmitral flow early velocity, compared to DTI E′,[65] also aid in identifying LV ischemic segments. The E′/A′ ratio is easy to recognize visually, and a ratio E′/A′ <1 is found in the majority of akinetic and hypokinetic segments.[64] Regional DTI diastolic abnormalities relate to global LV diastolic filling pattern, since patients with an abnormal transmitral E/A ratio <1 have more LV segments with DTI E′/A′ <1 than patients with normal transmitral E/A >1.[64]

Stress Echocardiography

Recognition of wall motion abnormalities on 2D echocardiography during stress echocardiography remains difficult and uncertain, especially if endocardial definition is suboptimal. There is a need for an objective method to quantify myocardial function. DTI S′ velocities recorded from the mitral annulus are more sensitive than 2D observation in detecting the myocardial response to dobutamine stress echocardiography. Coronary artery disease can be diagnosed accurately and objectively from off-line measurements of S′ velocities during dobutamine stress. S′ increased at a dose of 1 $\mu g \cdot kg^{-1} \cdot min^{-1}$, while 2D changes did not become apparent until 3 $\mu g \cdot kg^{-1} \cdot min^{-1}$.[66] The characteristic features of the ischemic myocardial response to dobutamine stress are diminished (≤50%–75% increase from baseline)[67] or show a lack of increase[68] of S′, development of prominent postsystolic shortening[63,69] and unchanged or slightly decreased E′.[69] At peak stress, S′ increases ≥100% in normal subjects.[70] The utility of DTI in unmasking coronary artery disease in the anesthetized, mechanically ventilated cardiac patient is worth studying, since S′ changes occur at relatively low dose infusion of dobutamine.

Diastolic Function and Estimation of Filling Pressures

The Doppler patterns of transmitral and pulmonary venous flow are influenced by loading conditions and do not always represent actual LV diastolic properties, such as relaxation.[71] E′ is related to LV diastolic properties, such as elastic recoil and relaxation, regardless of filling pressures or systolic function.[72] E′ changes in the same direction with preload when diastolic function is normal. This effect is less pronounced in ventricles with impaired relaxation, where E′ decreases and remains low even when ventricular filling pressure is high, as in patients with advanced diastolic dysfunction (pseudonormal and restrictive filling pattern) (Fig. 11).[32] This disassociation between preload and E′ is used to diagnose the different stages of diastolic dysfunction and estimate filling pressures by evaluating the transmitral E/A and DTI E′/A′ ratios together.[73]

a. The best evidence of normal diastolic function is a ratio E′/A′ >1 during a Valsalva maneuver (which decreases preload and minimizes its effect on E′).[74] Abnormal relaxation is the first

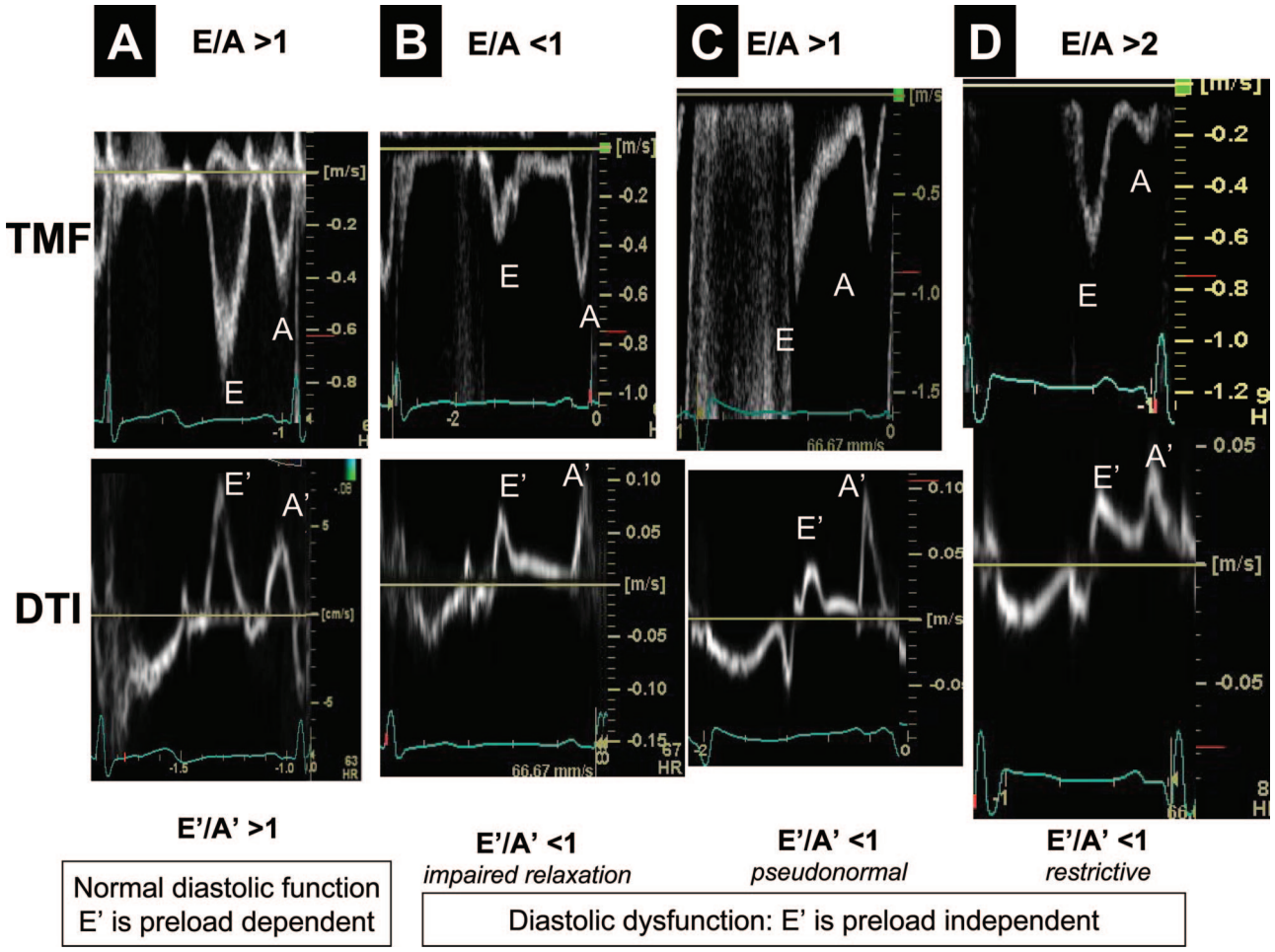


Figure 11. Evaluation of diastolic function with Doppler tissue imaging (DTI). A DTI ratio E′/A′ <1 is abnormal and used to differentiate between normal and pseudonormal transmitral flow (TMF) patters. (A) Normal diastolic function: E/A >1 and E′/A′ >1. (B) Impaired relaxation: E/A <1 and E′/A′ <1. (C) "Pseudonormal" pattern: E/A >1 and E′/A′ <1. (D) Restrictive pattern: E/A >2 and E′/A′ <1.

stage of diastolic dysfunction, and the ratio E′/A′ inverts (E′/A′ <1) (Fig. 11). This occurs at an early age (5th decade), even in the presence of a normal transmitral flow pattern.[75,76] As diastolic dysfunction progresses, E′ decreases and E′/A′ remains <1, despite any normalization of transmitral flow E/A due to augmented preload (E/A ≥1.5).[75] In the last stage of diastolic dysfunction (restrictive transmitral flow pattern E/A >2), an A′ >5 cm/s may predict a favorable response to afterload reduction.[77]

b. The combination of transmitral flow E (affected by both volume and relaxation) and DTI E′ (expressing relaxation but not volume) can be used to assess LV filling pressures (Fig. 12). The ratio E/E′ (measured in the same units) was associated with pulmonary capillary wedge pressure (PCWP) independent of the underlying pathology[47,72] or LV systolic function.[78] The mean PCWP can be calculated as

$$mean\ PCWP = (1.3 \times E/E') + 2^{47,79}$$

This ratio has been validated in awake patients in either atrial fibrillation[80] or sinus tachycardia.[79] The ratio E/E′ may be less predictive of LV filling pressures in the presence of normal LV function,[81] when both transmitral flow-E and E′ are preload dependent. In older patients with normal LV function, age and hypovolemia may jointly decrease E′ and increase the ratio E/E′ disproportionately to the filling pressures.[27] The site of DTI recording will have an impact on the ratio E/E′ as well. In a small number of cardiac surgical patients, the septal DTI velocities were decreased postoperatively, while the lateral mitral annulus velocities did not.[82] Since DTI measures regional velocity, any particular E′ should not be considered a direct measurement of global myocardial relaxation, especially in patients with coronary artery disease where LV relaxation is not uniform at baseline. However, the lateral mitral annulus site is rarely involved in ischemic heart disease,[47] and E′ recording at this location usually will represent LV relaxation. Therefore, to estimate LV filling pressures using the E/E′ ratio, the mid-esophageal four chamber view should probably be used to record the lateral mitral annulus site E′. The application of the E/E′ ratio in the anesthetized patient in the operating room merits further investigation.

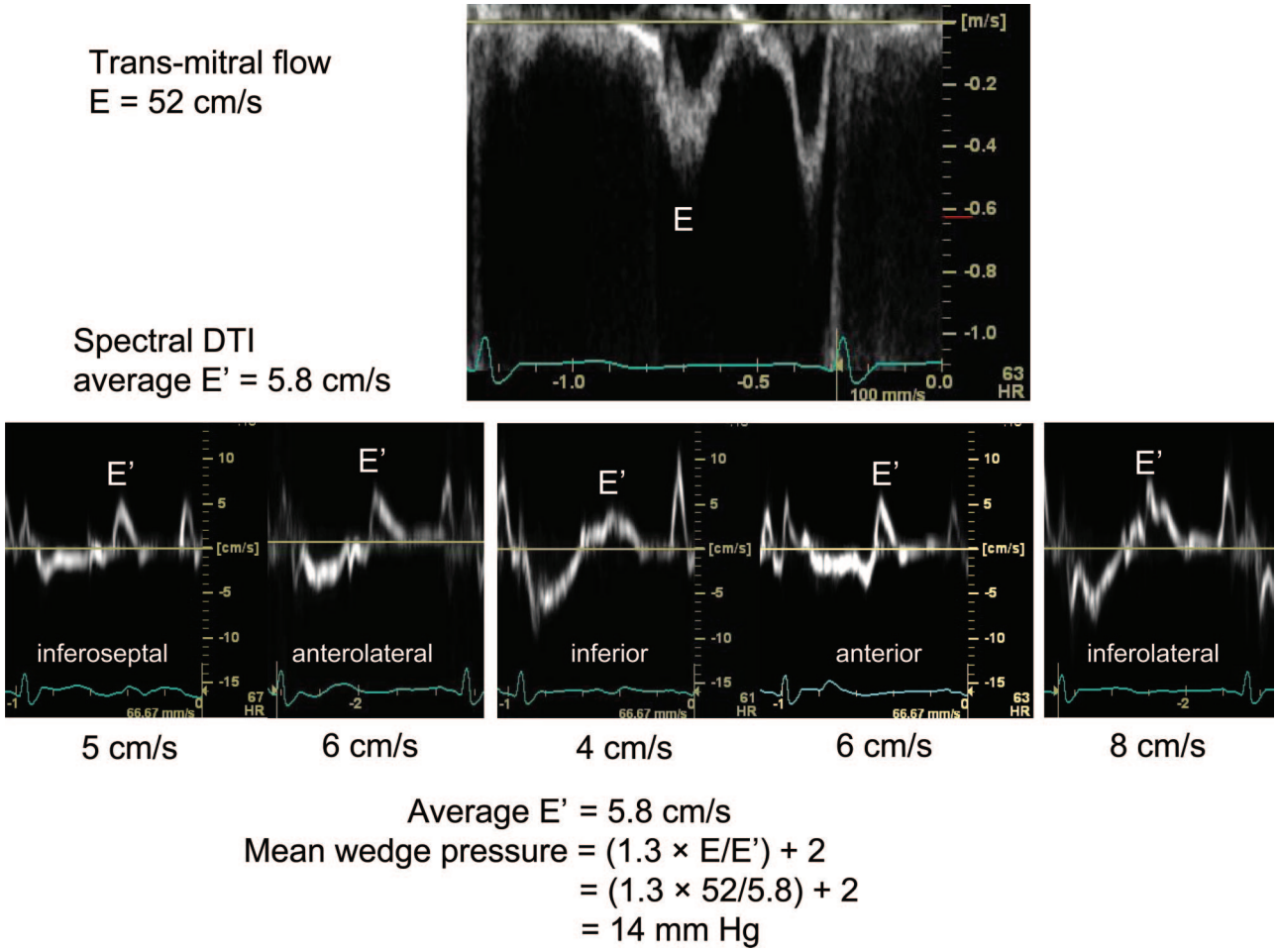


Figure 12. Estimation of filling pressures with Doppler tissue imaging (DTI). Mean capillary wedge pressure is calculated using the ratio of transmitral flow early velocity (E) and average early diastolic myocardial velocity (E'): mean wedge pressure = (1.3 × E/E') + 2 mm Hg. Transmitral flow is recorded with pulsed wave Doppler at the tips of mitral valve leaflets, and spectral DTI velocities from basal myocardial segments, next to the mitral annulus. The anteroseptal myocardial velocity was not recorded because of increased Doppler angle.

Valvular Heart Disease

DTI can be useful in detecting LV dysfunction in patients with regurgitant valvular lesions, who may be asymptomatic despite the presence of LV dilation and increased wall stress. Among asymptomatic patients with variable severity of aortic[83,84] or mitral[85] regurgitation, myocardial contractile reserve (diagnosed as an increase of LVEF >5% during exercise) was present if longitudinal S' (measured from the lateral or septal mitral annulus) was normal at rest. Among patients with stenotic valvular lesions, there is a significant inverse relationship between S', E', and E'/A' ratio and severity of aortic[86] and mitral stenosis.[87]

Heart Failure Prognosis

Significantly decreased DTI velocities (S' ≤3 cm/s, E' ≤3 cm/s, A' ≤4 cm/s) and E/E' >20 independently identified those heart failure patients at risk of cardiac death.[88,89]

Cardiomyopathies and Constrictive Pericarditis

DTI may be the diagnostic tool of choice when conventional echocardiography cannot differentiate physiologic (the result of exercise in healthy individuals) from pathologic hypertrophy, or constrictive pericarditis from restrictive cardiomyopathy. In hypertensive patients, LV hypertrophy is pathologic if DTI demonstrates asynchronous regional systolic contraction and relaxation, and abnormal diastolic function,[10,90,91] postsystolic shortening suggestive of subendocardial ischemia,[92] or decreased velocities.[93] Both constrictive pericarditis and restrictive cardiomyopathy have similar clinical (heart failure) and echocardiographic presentation (restrictive transmitral flow pattern). In constrictive pericarditis, E' velocity is normal, indicating preserved elastic recoil, even when the respiratory variation in transmitral E wave is blunted or absent. However, E' is reduced in restrictive cardiomyopathy as a result of intrinsic myocardial disease.[94]

RV Function

The echocardiographic assessment of RV function is cumbersome, and measurement of volumes and calculation of EF is inaccurate because of anatomic (irregular shape, presence of trabeculations, different embryologic origin of the inflow and outflow tracts) and physiologic (load dependency and pericardial influence) factors. DTI velocities from the free RV wall

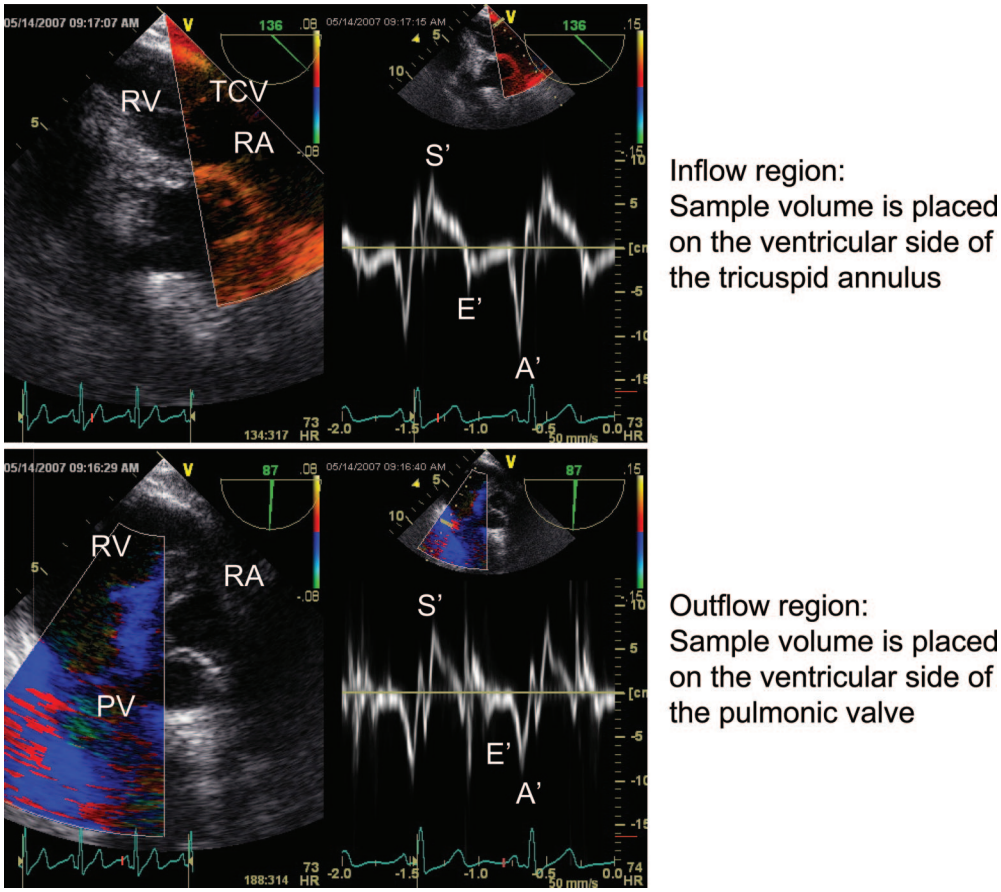


Figure 13. Doppler tissue imaging of the right ventricle (RV). The RV inflow (top) and outflow (bottom) regions are examined with color (left) and pulsed wave (right) Doppler tissue imaging, in the deep transgastric RV view. PV = pulmonic valve; RA = right atrium; TCV = tricuspid valve.

(Fig. 13 and Video 5), lateral to the tricuspid annulus, have been used to evaluate RV function.[95] Although easy to perform, DTI of the tricuspid annulus represents only the longitudinal myocardial fiber function and is affected by translational motion and rotation of the whole heart.[95] The excursion of the tricuspid annulus is greater when compared to the mitral annulus because of the shape of the ventricle and the DTI velocities are significantly higher in the RV.[96] In contrast to the LV, only the RV E′ tissue velocities correlate with age.[97] A tricuspid annulus S′ <10–11.5 cm/s is associated with RVEF <45%.[95,98] As is the case with LV velocities, TTE- and TEE-recorded tricuspid annulus velocities may not be comparable because of different views, DTI modality (color vs spectral) and/or potential effect of general anesthesia. The RV free wall tricuspid annulus velocities of precoronary artery bypass graft patients were higher with TTE of the apical four chamber view than with TEE of the modified deep transgastric LV view[99] and were not related to hemodynamics. Attempts to correlate the mean right atrial pressure with the E/E′ ratio derived from the transtricuspid flow and the lateral tricuspid annulus in anesthetized patients are not always successful.[100,101] DTI can have diagnostic value in RV infarction. A low S′ identified those patients with RV myocardial infarction[102–104] or proximal right coronary artery involvement,[104] while an S′ <8 cm/s was predictive of cardiac death or rehospitalization at 1 yr.[103]

Mechanical Dyssynchrony

In normal synchronous hearts, segmental S′ peak almost simultaneously, whereas in dyssynchronous hearts, the lateral segments peak considerably later than the septal which results in insufficient ejection. Pacing of the affected region allows synchronized mechanical activity and improves ejection.[105] Mechanical dyssynchrony as determined by longitudinal DTI velocities may be superior to electrocardiography in predicting response to cardiac resynchronization therapy. The most recent guidelines suggest the use of color DTI for recognition of mechanical dyssynchrony.

CONCLUSION

Currently, DTI with pulsed wave Doppler is a rapid method to obtain direction, timing, and velocity of regional longitudinal myocardial motion and quantify systolic and diastolic function. While extensively investigated in awake patients, the potential intraoperative applications need to be verified. Although DTI provides regional measurements, sampling from different sites will help compensate for any differences, facilitating the evaluation of global EF and diastolic

function and calculation of filling pressures. Repeated DTI observations in the same patient enable the detection of regional ischemia (decrease in S′ and E′ and E′/A′ <1), and appearance or detection of postsystolic shortening is a sensitive index of ischemic but viable myocardium. DTI has also been used to detect subclinical ventricular dysfunction in asymptomatic patients with valvular disease and differentiate physiologic from pathologic hypertrophy and distinguish constrictive pericarditis from cardiomyopathy. DTI is based on Doppler, and its major limitations are due to mismatch between the imaging plane and the direction of myocardial motion and to tethering of neighboring segments. Doppler strain and speckle tracking are newer techniques that may overcome some of those limitations. Doppler strain measures local myocardial deformation from the velocity gradient between two sample points along the myocardial wall. Although not limited by tethering, since measurements are in reference to myocardium and not to an immobile transducer, it is still subject to the Doppler angle limitation.[17,106] Speckle tracking derives myocardial velocity in two dimensions from tracking of acoustic markers, produced by the interaction of ultrasound with tissue. Speckle tracking is not based on Doppler and measurements are independent from insonation angle and tethering.[17] In addition, it is automated and provides regional as well as global measurements. Both Doppler strain and speckle tracking are considered research techniques and have not found wide-spread acceptance in everyday clinical practice. Currently, if the limitations are taken into consideration, DTI can be a helpful diagnostic modality, offering quick, real time insights into clinical diagnostic challenges.

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