Review Article

# Strain and strain rate: An emerging technology in the perioperative period

**Vishwas Malik, Arun Subramaniam, Poonam Malhotra Kapoor**
Department of Cardiac Anaesthesia, CTC, AIIMS, New Delhi, India

## ABSTRACT

Newer noninvasive parameters are being used for perioperative detection of myocardial ischaemia. TDI and global strain rate are some of these parameters. TDI signal is a modification of the routine Doppler flow signal. It is obtained by using thresholding and filtering algorithms that reject echoes originating from the blood pool (by-passing the high pass filter). Set-Up of the machine by activating the TDI function allows decreasing the system gain using a low pass filter and eliminates the signal produced by blood flow. Doppler shift obtained from myocardial tissue motion are of higher amplitudes (reflectivity 40 dB higher) and move about 10 times slower than blood (velocity range: 0.06 to 0.24 m/s). Speckle tracking echocardiography (tissue tracking, 2D strain) utilizes routine gray-scale 2D echo images to calculate myocardial strain. Interactions of ultrasound with myocardium result in reflection and scattering. These interactions generate a finely gray-shaded, speckled pattern (acoustic marker). This speckled pattern is unique for each myocardial region and relatively stable throughout the cardiac cycle. Spatial and temporal image processing of acoustic speckles in both 2D and 3D allows for the calculation of myocardial velocity, strain, and Strain rate.

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## INTRODUCTION

Recently, noninvasive measurement of regional left ventricular (LV) function has gained significance to diagnose the pathology and quantify the extent of disease process. This, in turn, can guide the clinician to modify the therapeutic intervention and predict the postoperative outcome of the patient. It has the potential to become relevant in the perioperative period for risk stratification, prognostication, and determine the adequacy of surgical repair. However, it has to be noted that the assessment of regional function is more difficult than assessing the global function; therefore, it remains subjective and requires significant training.

## CARDIAC COMPUTED TOMOGRAPHY AND MAGNETIC RESONANCE IMAGING

Magnetic resonance imaging (MRI) could guide us in the assessment of the regional LV function assessment. However, the risk of radiation and time taken to acquire the images has made echocardiography as the most convenient tool. The other advantage of echocardiography and, in specific, transesophageal echocardiography (TEE) is that it can be employed in the perioperative setting and can thus provide a real-time picture of the regional LV function without disturbing the surgeon. Echocardiographic strain imaging is a technological advancement that can objectively quantify regional myocardial function.[1,2] Initially developed as tissue Doppler imaging (TDI),

**Address for correspondence:** Dr. Poonam Malhotra Kapoor, Department of Cardiac Anaesthesia, CTC, AIIMS, New Delhi - 110 029, India.
E-mail: drpoonamaiims@gmail.com



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which was developed primarily as means of calculating strain and strain rate (SR) has now been expanded to the technology of speckle tracking computer processing.[3,4] In this article, we will be reviewing the techniques of strain imaging, their advantages and pitfalls, and the application of strain imaging in various disease processes.

## WHAT IS VENTRICULAR STRAIN AND STRAIN RATE?

The word "strain" in echocardiography implies regional myocardial deformation. The rate at which this change occurs is called SR. Deformation in basic sense may denote lengthening, shortening, or thickening. The readers can refer to the articles written by D'Hooge *et al*.[2] and Mor-Avi *et al*.[5] to understand the technical features of strain. In short, myocardial regional motion by echocardiography divides strain into four types namely longitudinal, radial, circumferential, and rotational [Figure 1]. Mathematically, strain (E) can be denoted as ΔL/L0, where ΔL is the change in length and L0 is the original length. To completely define the deformation of three-dimensional (3D) objects, for example, myocardial segments, all nine strain components (3 normal strains and 6 shear strains) must be defined. Echocardiographic deformation imaging allows one-dimensional measurements based on TDI and two-dimensional (2D) as well as 3D strain measurements based on speckle tracking imaging [Figure 1].[1,6]

## BASIC PRINCIPLE OF TISSUE DOPPLER IMAGING

TDI signal is a modification of the routine Doppler flow signal. It is obtained using thresholding and filtering algorithms that reject echoes originating from the blood pool (by-passing the high pass filter). Setup of the machine by activating the TDI function allows decreasing the system gain using a low-pass filter and eliminates the signal produced by blood flow. Doppler shift obtained from myocardial tissue motion is of higher amplitudes (reflectivity 40 dB higher), and move about 10 times slower than blood (velocity range: 0.06–0.24 m/s) [Figures 2 and 3].

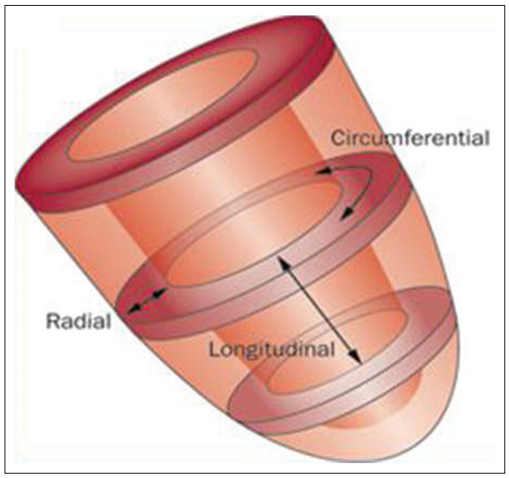


**Figure 1:** The three components of normal strain often referred to as principal strains, diagrammatically represented in this figure. Three perpendicular axes – longitudinal, circumferential, and radial represent the geometric coordinates of the left ventricle

## UNDERSTANDING OF THE NORMAL PATTERN OF MYOCARDIAL MOVEMENT IS NECESSARY FOR COMPREHENSIVE ASSESSMENT OF TISSUE DOPPLER IMAGING DATA

### How to get image in tissue Doppler imaging

TDI of a midesophageal (ME) four-chamber view is acquired as a full-sector view; frame rate is 100 Hz and same image is acquired, but the sector is narrowed down to improve frame rates. Note that frame rates have increased from 100 Hz to 223 Hz [Figures 4 and 5].

### Basic principle of tissue Doppler imaging

A small pulsed wave sampling volume measures the velocities of the myocardium as it moves toward and away from the transducer. TDI will underestimate the myocardial velocities if the angle of interrogation is not parallel to motion. Patients with normal global LV function have systolic velocities >7.5 cm/s, whereas velocities ≤5.5 cm/s indicate LV failure. Systolic velocities <3 cm/s are associated with a significantly increased risk of cardiac death within 2 years [Table 1].

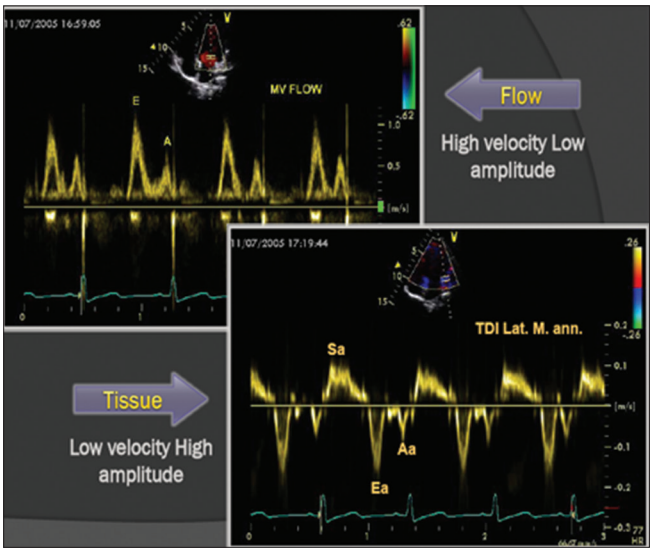


**Figure 2:** Velocity range

## COLOR TISSUE DOPPLER

Doppler can be color-coded to provide a color map of blood flow patterns; in the same way, tissue Doppler can be color-coded to display myocardial velocities; red depicting positive velocities and blue for negative velocities. The display is of real-time 2D gray-scale images overlain by color-coded myocardial velocities. Placing markers at various points along a ventricular wall produces a graphical representation of velocity against time called curved M-mode. Advantage over tissue Doppler is the ability to utilize spatial information and, therefore, assess regional and global LV function. Advantage over 2D echocardiography is that the

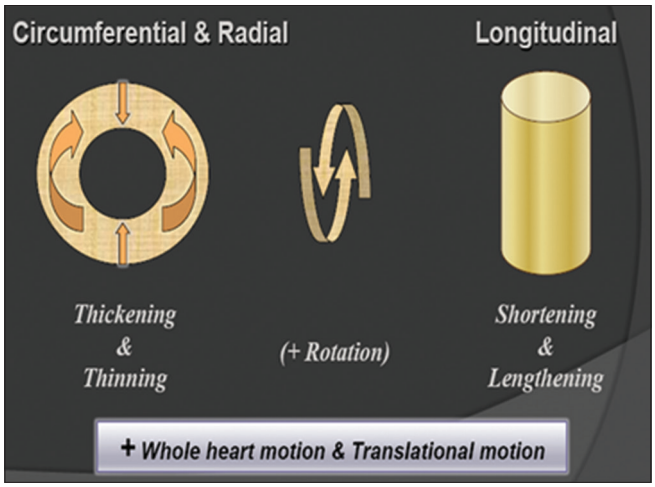


**Figure 3:** Understanding of the normal pattern of myocardial movement is necessary for comprehensive assessment of tissue Doppler imaging data

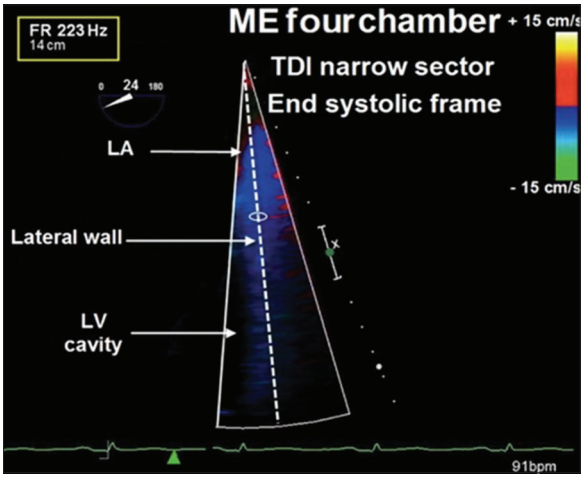


**Figure 5:** Same images are acquired, but the sector is narrowed down to improve frame rates. Note that frame rates have increased from 100 Hz to 223 Hz

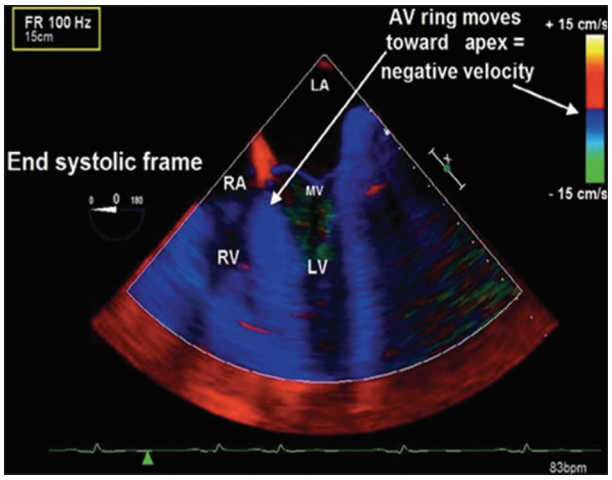


**Figure 4:** Tissue Doppler imaging of a midesophageal four-chamber view acquired as a full-sector view; frame rate is 100 Hz

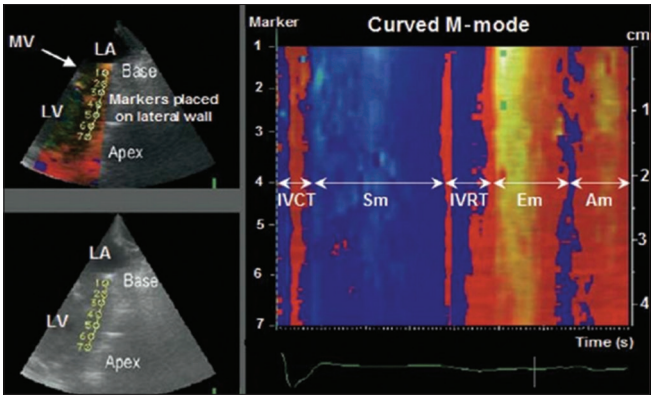


**Figure 6:** Color tissue Doppler

**Table 1: Factors affecting tissue Doppler imaging velocity measurements**

| Parameter | Tissue Doppler velocities (cm/s) | | | |
|---|---|---|---|---|
| Age differences in cardiac | <65 years | | >65 years | |
| | Average Sa=6.7±1.8 | | Average Sa=5.7±1.7 | |
| Gender differences in healthy subjects with mild hypertension | Male | | Female | |
| | Sa lateral wall=10.2 (9.6-11.0) | | Sa lateral wall=8.9 (8.4-9.5) | |
| Point of interrogation i.e., longitudinal velocity gradient (healthy subjects) | Septum | Lateral | Posterior | Anterior |
| | Sa=5.7±1.6 | Sa=8.7±2.4 | Sa=6.4±1.1 | Sa=7.7±2 |
| | Sm=4.3±1.1 | Sm=7.9±2.4 | Sm=5.4±1.2 | Sm=6.3±2.2 |
| | Apex=3.1±1 | Apex=7.1±2.4 | Apex=4.2±1.4 | Apex=4.8±2.5 |

endocardial borders do not need to be clearly identified; dropout in walls which lie parallel to the path of the ultrasound beam is no longer a limitation in assessing LV function [Figures 5 and 6].

## TISSUE DOPPLER IMAGING AND STRAIN

TDI is regarded as an accurate echocardiographic tool to quantify the cardiac function.[7,8] TDI utilizes the Doppler principle to convert ultrasound frequency shifts to velocity data. TDI derives strain from the velocity data by the following equation SR (E) = (Va − Vb)/L × cosθ, where Va is the velocity at point a, Vb is the velocity at point b, L is the length which is usually assumed as 10 mm, and cos is the cosine of the angle between the ultrasound beam and the direction of myocardial movement.

Integration of SR yields strain, the normalized change in length between these 2 points. The calculation of strain by TDI requires the direction of the ventricular motion to be in line with the ultrasound beam. The principal drawback in TDI was the alignment of the Doppler scans line with the myocardial motion.[1,8] The Doppler angle correction analysis program has overcome this limitation.[9] In the operating room, the ME 4-chamber, 2-chamber, and the long axis views can be obtained to estimate the strain and SR by TDI.

## LIMITATIONS OF TISSUE DOPPLER IMAGING

With TDI, we are diagnosing advanced dysfunction. There are several disadvantages of TDI.[10] First of all, they are derived from single dimension velocity measurements, but the myocardium deforms simultaneously in three dimensions. It is also important to know that the comparison of adjacent velocities is highly sensitive to signal noise. This can be improved by increasing sample distance but only in exchange for lower spatial resolution. Finally, data acquisition and processing are time-consuming. However, TDI can be a valuable noninvasive tool for routine clinical use to evaluate the myocardial contractile function.

## SPECKLE TRACKING AND STRAIN CALCULATION

Speckle tracking is a non-Doppler technology that has recently been developed to quantify the strain and SR.[11,12] This technology uses the routine gray-scale images and calculates the strain employing a postprocessing computer algorithm.[13,14] In short, speckles, which are the natural acoustic markers distributed throughout the myocardium, are tracked from frame to frame. Special software allows spatial and temporal image processing with recognition and selection of such elements on ultrasound images. The geometric shift of each speckle represents local tissue movement. When frame rate is known, the change in speckle position allows determination of its velocity. Thus, the motion pattern of myocardial tissue is reflected by the motion pattern of speckles. By tracking these speckles, strain and SR can be calculated. At present, the optimal frame rate for speckle tracking seems to be 50–70 frames per second (FPS), which is lower compared to TDI (>180 FPS). This could, however, result in under-sampling, especially in patients with tachycardia [Figure 7].

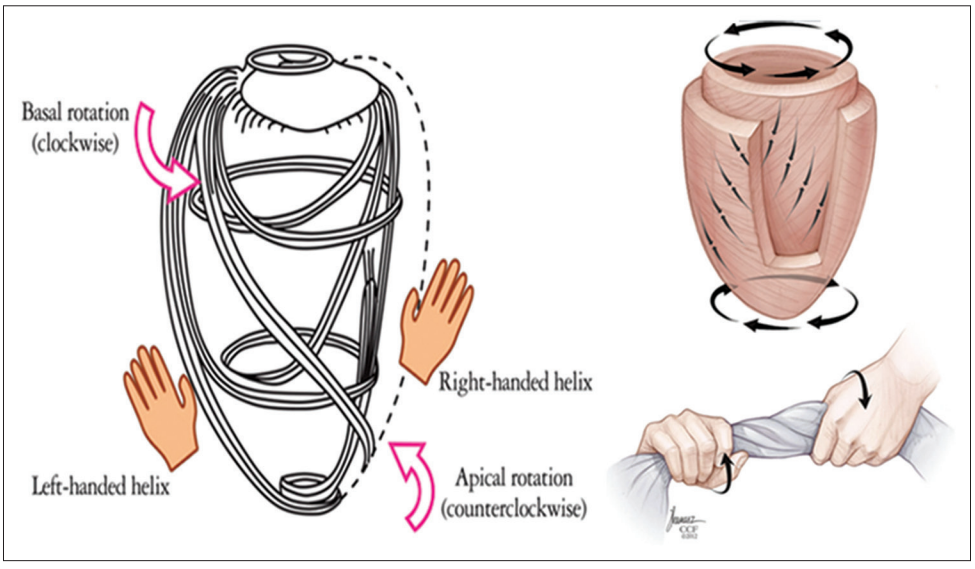


**Figure 7:** Myocardial fibers in the subepicardium helically run in a left-handed direction, fibers in the mid layer run circumferentially, and fibers in the subendocardium helically run in a right-handed direction

Using higher frame rates could reduce the under-sampling problem, but reduces the spatial resolution and suboptimal tracking.[15] Low frame rate increases the spatial resolution, but because speckle tracking software uses a frame-by-frame approach, this could also lead to poor tracking.[16,17] The advantage of this technique is that it measures the strain in 2D, thus making it angle-independent. Similarly, the reproducibility of strain measurements is better than TDI as documented by Ingul *et al*.[18] One major limitation of this technique is the need for high-quality images to perform the strain calculation. Spatial and temporal image processing of acoustic speckles in both 2D and 3D allows for the calculation of myocardial velocity, strain, and SR.

## THREE-DIMENSIONAL SPECKLE TRACKING AND STRAIN CALCULATION

A recent approach to quantify the ventricular volume and dyssynchrony is 3D speckle-tracking echocardiography (STE). The interest in 3D TEE stems from the fact that 2D echocardiography is restricted to a single plane and is subjected to beat-beat variability. As demonstrated by Pérez de Isla *et al*.,[19] 3D wall motion tracking system is better than 2D system for the assessment of myocardial strain. For a detailed description on how to calculate the strain using a 3D echocardiography, the readers can refer to the article by Gorscan and Tanaka.[20] Briefly, the 3D system utilizes a pyramidal volume from a full volume dataset. Using the TEE, this can be acquired during a period of breath-hold from the mid esophageal 4-chamber view. A stable image is important for a successful 3D evaluation. The major limitations of 3D echocardiography are the slow temporal resolution and motion artifacts. Similarly, the spatial resolution of 3D images is not as clear as 2D images. Recent revision in the 3D software has permitted the acquisition of a better image quality with 3D TEE. It helps in the identification of subtle regional and global contractile abnormalities, identification of dyssynchrony, and evaluation of diastole mechanics of the heart and prognostic value.

**Table 2: Normal strain and strain rate patterns in different segments**

| | Wall | Average value in normal subjects |
|---|---|---|
| Longitudinal strain (%) | Lateral, Posterior, anterior | 18±5 |
| | Septal | 22±5 |
| Longitudinal strain rate (/s) | Anterior, septal | 1.5±0.4 |
| | Lateral, posterior | 1.2±0.3 |

## STRAIN AND STRAIN RATE

An increase in myocardial length is denoted by a positive value, whereas a decrease in the myocardial length is denoted by a negative value. In the ME long-axis views, as the ventricle contracts, the longitudinal length becomes smaller and ε and SR values will be negative. Conversely, during diastole, the ventricle elongates and ε and SR will have positive values. However, note that during systole in a short axis view (SAX) view of the LV, the myocardium thickens, so that the measured myocardial length (thickness) increases and ε and SR will have positive systolic values, with negative values during diastole as the myocardium thins out [Table 2]. Global longitudinal strain (LS) is easily measured in a 2-chamber and 4-chamber view on TEE [Video 1].

## CLINICAL APPLICATIONS OF STRAIN AND STRAIN RATE IN CARDIAC DISEASES

Clinical validation of strain and SR by echocardiography has been validated using MRI.[21] Strain and SR measurements appeared to be sensitive indicators for various cardiac diseases, including diabetes, myocardial ischemia, arterial hypertension, valvular heart diseases, and also very useful for the assessment of myocardial damage after infarction, evaluation of myocardial revascularization efficiency, and prediction of patient outcome with heart failure.[22-25] Abnormal speckle parameters are found in:

- Cardiomyopathies
- Valve disease
- Ischemic heart disease
- Therapy-induced disorders.

## WHAT PARAMETERS CAN BE OBTAINED?

The parameters obtained with speckle tracking and SR are displacement, strain, SR, rotation, twist, twist rate, untwist, untwist rate, and torsion.

## ISCHEMIC HEART DISEASE AND STRAIN IMAGING

The addition of strain imaging has increased the sensitivity of TEE to the detection of specific patterns of ischemia. It should be borne in mind that ischemic wall motion abnormalities can result in passive motion due to recoil and tethering from adjacent nonischemic

segments. Strain imaging can differentiate active from passive motion, which is difficult on visual examination. Skulstad *et al*. used strain imaging to explain the pattern of postsystolic shortening with coronary artery occlusion.[26] Weidemann *et al*.[27] proposed a postsystolic strain index that could predict the extent of transmurality of myocardial infarction.

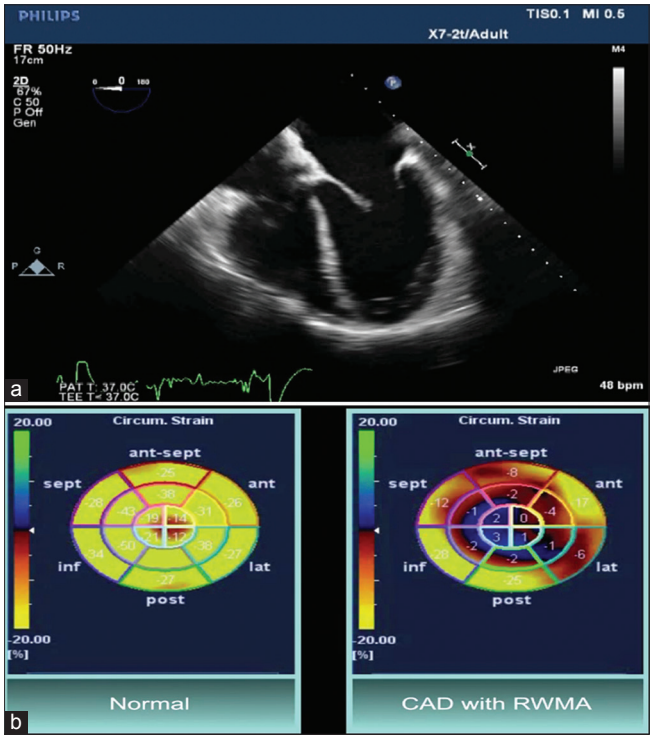


**Figure 8:** (a) How to estimate strain rate, stepwise in a 2-chamber. (b) Coronary artery disease with regional wall motion abnormalities in different segments

Similarly, Lim *et al*. correlated the time-to-peak TDI strain with the percentage of transmural infarct.[28] [Figures 8a and b, and 9].

## ASSESSMENT OF MYOCARDIAL VIABILITY

The assessment of myocardial viability is another useful property of strain imaging. Bansal *et al*.[29] compared myocardial tissue velocity imaging (TVI) and STE for prediction of viability at dobutamine echocardiography in patients who were scheduled for coronary revascularization. They concluded that the combination of tissue velocity or speckle tracking imaging methods with dobutamine echocardiography can predict viability, with accuracy being the maximum at low-dose dobutamine. They also proposed that TVI measures can predict viability in both anterior and posterior circulations, but STE measurements predict viability only in the anterior circulation, thus making TVI superior to STE. Likewise, Hanekom *et al*.[30] examined patients with ischemic heart disease undergoing viability testing by dobutamine echocardiography. They compared the wall motion abnormalities by both visual and strain imaging. At 9 months following coronary revascularization, visual examination had a modest sensitivity and specificity. This was significantly enhanced when strain imaging was added to visual examination. Strain imaging has also been used to aid in the diagnosis of diastolic dysfunction in patients with preserved ejection fraction. Kasner *et al*.[31] concluded that SR imaging

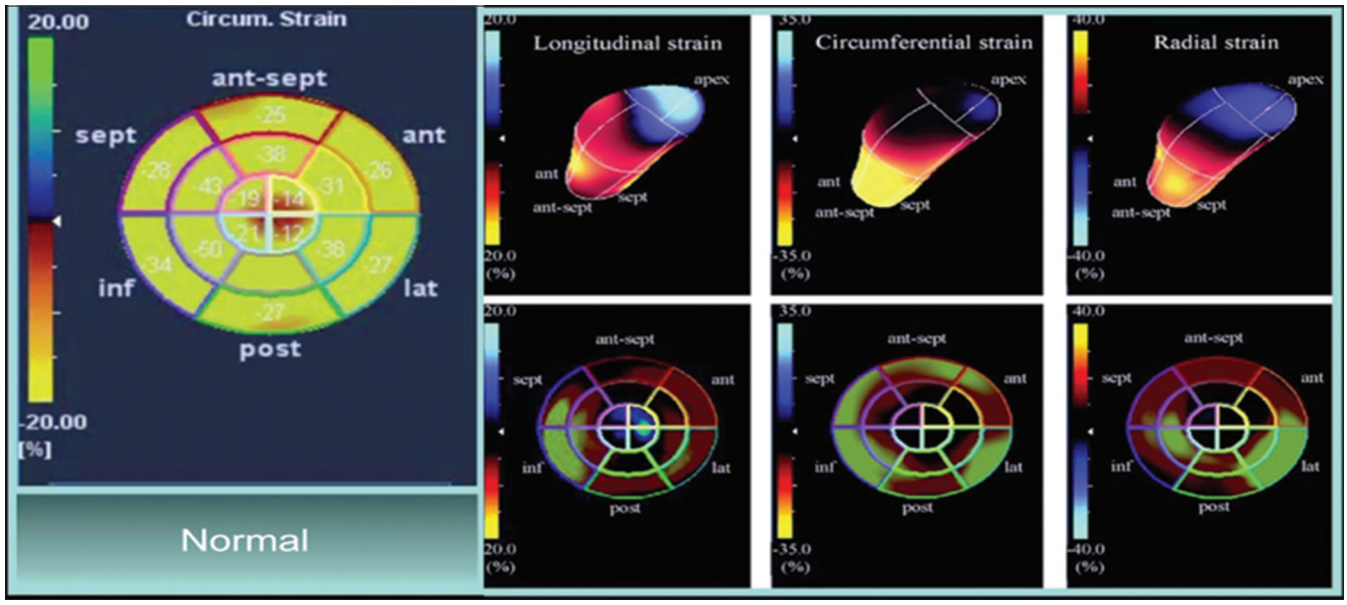


**Figure 9:** Left anterior descending occlusion in 3 different strain types

as accurate as TDI in detecting increased LV stiffness in preserved ejection fraction. Seo *et al*.[32] in their study reported the usefulness of 3D speckle tracking in assessing myocardial ischemia. They opined that 3D speckle tracking has a tremendous potential to define LV mechanics. Ternacle *et al*.[33] concluded that 3D speckle tacking diagnosed myocardial deformation due to ischemia before the appearance of wall motion abnormality as shown in Figures 8a and 9.

## STRAIN IMAGING AND VALVULAR HEART DISEASE

Strain imaging can play a pivotal role in valvular heart diseases when compared to conventional means alone. In patients with aortic stenosis and normal LV function, Delgado *et al*.[34] demonstrated a decreased speckle tracking strain that improved after aortic valve replacement. Likewise, Tayyareci *et al*.[35] showed a decrease in myocardial strain in patients with aortic regurgitation and a normal ejection fraction. Likewise, a preoperative left atrial (LA) strain imaging can help us in predicting the degree of LA fibrosis and remodeling after mitral valve replacement.[36] Kanellopoulos *et al*.[37] compared the LS values in patients with bicuspid aortic valve (BAV) disease and in those with degenerative aortic valve disease. They concluded that patients with BAV have a structural myocardial disease, irrespective of the degree of stenosis as compared to degenerative valve disease. These studies highlight the importance of TDI and speckle tracking in the detection of subclinical LV dysfunction in patients with valvular heart disease.

## STRAIN IMAGING AND CARDIAC DYSSYNCHRONY

Patients with ischemic heart disease may also have a component of ventricular dyssynchrony, which can have a negative impact on ventricular mechanics. Various types of speckle tracking dyssynchrony approaches have been suggested that can be derived from transgastric views. Radial and transverse strains reflect myocardial thickening whereas longitudinal and circumferential strains denote myocardial shortening. About 30% of patients selected on the basis electrocardiogram do not respond to cardiac resynchronization therapy (CRT) and there is an increasing evidence that the main predictor of responsiveness to CRT is mechanical rather than electrical dyssynchrony.[38,39] Speckle tracking and resynchronization study was the first to associate speckle tracking dyssynchrony with ejection fraction response and long-term survival after CRT.[40] 2D strain imaging by speckle tracking and TDI has been proved to be useful for both the selection of patients who might be benefited from CRT and the evaluation of CRT efficiency.[41-43] An important aspect for CRT effectiveness is its dependency on the LV lead position. To find out the optimal LV lead position is, therefore, a major goal, and recent studies have shown that 2D-strain imaging is a useful tool for this purpose.[44] Since LV dyssynchrony is a 3D phenomenon, 3D speckle tracking is emerging as a tool to detect and quantify dyssynchrony. Tanaka *et al*. have reported the usefulness of 3D speckle tracking to successfully quantify LV dyssynchrony.[45] There appears a clear potential for this modality to be more accurate than 2D methods and further studies are going on.

## MISCELLANEOUS APPLICATIONS OF STRAIN IMAGING

Strain and SR have found application in the assessment of myocardial function in cases of arrhythmogenic RV dysplasia (ARVD), hypertrophic cardiomyopathy (HOCM), and drug-induced cardiomyopathy [Figure 10]. Vitarelli *et al*.[46] evaluate the potential utility of STE at rest and after stress to predict ARVD. The RV-LV peak systolic LS was obtained in the basal, mid, and apical segments in the apical 4-chamber view using STI. An exercise stress-echocardiographic test was undertaken using bicycle ergometry with the patient in the supine position for all patients, and the indexes were assessed at peak effort. They concluded that STI at rest and during stress might enable quantitative assessment of RV function and the detection of ARVD. Speckle tracking has been recently studied in assessing the changes in the right heart due to pulmonary hypertension. Li *et al*. compared[47] patients with pulmonary hypertension to 31 healthy controls by assessing multiple parameters that are thought to be predictive of RV changes. Kato *et al*.[48] reviewed that the TDI of LS of < 10.6% was highly specific for the detection of HOCM. Likewise, Yajima *et al*.[49] suggested that peak LS can distinguish fibrotic from nonfibrotic LV in cases of HOCM.

## THE RIGHT VENTRICULAR FUNCTION

The role of 3D speckle tracking imaging in assessing the RV function has been studied by Atsumi *et al*.,[50] who noted that in patients with RV dysfunction, 3D STI indicated low peak systolic area change ratio in the damaged area. Strain for detection of ischemic Cardiomyopathy.

## FOUR-DIMENSIONAL STRAIN IMAGING

Four-dimensional (4D) strain is a postprocessing research tool that tracks inherent features in a 3D image from frame to frame over time. 4D strain uses a tracking algorithm based on frame-to-frame block matching performed in three dimensions. This involves successively searching for a match between 3D patterns found in one 3D frame and in the next [Figure 11]. Calculation is performed after tracking all the areas inside a region of interest that covers the LV myocardium. Utilizing the tracking results, 4D strain derives several parameters, including longitudinal, circumferential and radial strain, as well as area strain. The 4D strain tool has been validated in a study using 22 simulated datasets with known deformation.[51]

## CONCLUSION

TDI measures myocardial velocity. SR is the difference between these velocities. Strain is integrating SR over time. Strain imaging, also referred to as deformation imaging, has been used to track and quantify regional TDI myocardial function, of which speckle tracking is the most recent version which measures myocardial velocity between two points. SR is the difference between these two velocities. Speckle tracking overcomes angle dependency and passive myocardial movement.

- PW TDI: Measures peak velocity
- Color TDI: Measures mean velocity.

We can now better understand the pathophysiology of ischemic heart disease, detect subclinical ventricular dysfunction in valvular heart disease, and assessment of dyssynchrony in CRT candidates. 3D and 4D strain imaging have emerged as a further advance to provide a better understanding of the various disease processes. Strain imaging with its advancements is going to be an important tool in the perioperative management of cardiac surgical patients for better outcomes, and it is

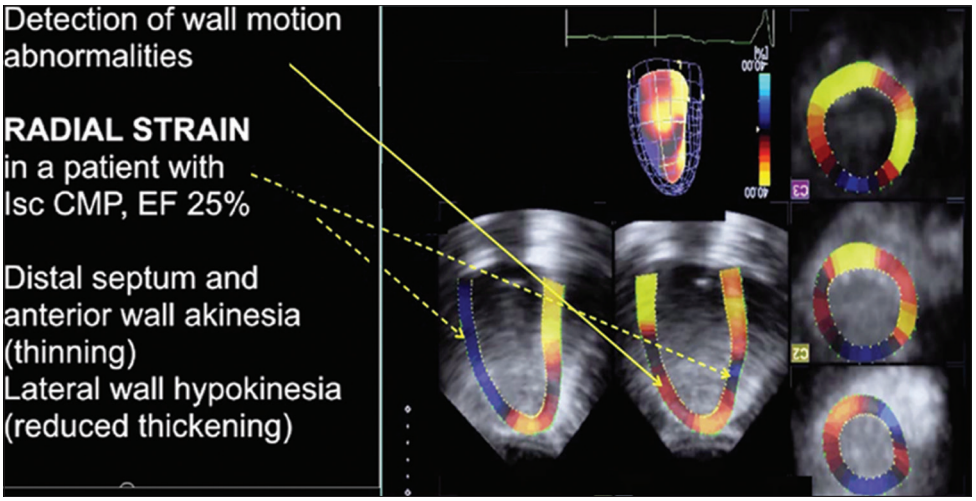


**Figure 10:** Ischemic cardiomyopathy and radial strain in a patient with 25% ejection fraction

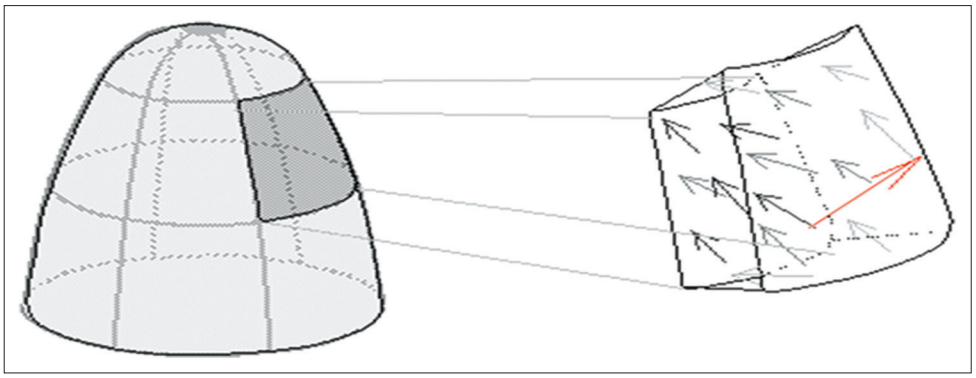

**Figure 11:** Illustration of a segment of the left ventricle with tracking results from all areas through the heart wall from endocardium to epicardium. The arrows indicate the estimated displacement from one frame to the next. The arrow in red illustrates an outlier caused by an erroneous match

time cardiac anesthesiologists get acquainted with this emerging and exciting technology.

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### Conflicts of interest

There are no conflicts of interest.

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