New echocardiographic techniques for the assessment of cardiac function

Maria FLORESCU MD, Dragos VINEREANU MD, PhD, FESC, Mircea CINTEZA MD, PhD

aEmergency University Hospital, Bucharest, Romania
b“Carol Davila” University of Medicine and Pharmacy, Bucharest, Romania

I. INTRODUCTION

The cardiac function is classically defined as the ability of heart to work and keeping working sufficiently, in order to maintain an optimal cardiac output. This is due to the development of cardiac force to generate cavity pressure and, then, to the deforming of myocardial fibres to displace cavity volume in the ejection phase (1). The transmission of the force from the fibres towards the ejection depends on several factors. First of all, there is a particular geometry of the ventricles – ellipsoid shape for the left ventricle and crescent one for the right ventricle, probably related to the pressure differences between left and right cavities. Second, myocardial fibers are disposed in a complex architecture and orientation – a subendocardial layer, which is longitudinally disposed, a subepicardial layer, which is radial disposed, and a circumferential layer, in the midwall (2). Finally, the elasticity of the wall and the all segment synchronous interaction, are important determinants of cardiac performance.

Therefore, when we quantify cardiac function, two features of the muscular fibers are very important from a mechanical point of view: motion and deformation (3). If a force acts upon a moving rigid body, this force will result in a change of the way the object moves. Thus, the object has a translational velocity, but the shape remains unchanged. Over time, the body will change position – displacement. On the other hand, the force acting on an elastic objects can induce shape changing of the object – deformation. Put all this in the wall of a heart, we can describe this deformation in the complex 3D settings of the heart – in systole: longitudinal shortening, radial thickening, and circumferential shortening; and on contrary in diastole: longitudinal lengthening, radial thinning, and circumferential lengthening. Recently, there has been described another type of left ventricular deformation – left ventricular torsion (4). Due to the complex disposition of the muscular fibers across the left
ventricular wall (figure 1), the shortening of obliquely oriented left ventricular fibers determines a wringing motion responsible for torsion. Torsion or twist is defined by the opposite basal and apical rotation. Thus, the apex rotates counter clockwise relatively to the base (figure 2), playing an important role in ejection and in storage of the energy at the end of the systole, the release of this energy during the early diastole resulting in ventricular suction.

In present, non-invasive assessment of cardiac function represents a major goal in clinical cardiology. To implement this, several methods, based on different imaging modalities have been proposed. Echocardiography is currently the first-line imaging modality for evaluating the cardiac function. Using conventional echocardiography, cardiac function is most often assessed visually, by volumes, global ejection fraction or diastolic function. Myocardial thickening and segmental wall motion can also be assessed, but these parameters are actually visually estimated on the 2D echocardiography. Therefore, this qualitative approach on the cardiac function has important limitations, resulting in large intra-and interobserver variability. Furthermore, conventional echocardiography estimates only radial function of the myocardium, whereas others – longitudinal, circumferential and torsion – are ignored. Recently, new echocardiographic techniques have emerged as a quantitative tools to evaluate regional myocardial function, both motion and deformation. This paper will discuss the most important new echocardiographic techniques – Tissue Doppler Imaging, Speckle Tracking Imaging, and 3D and 4D Echocardiograph, and emphasizes the clinically utility of these methods.

II. TISSUE DOPLER IMAGING

For years, the non-invasive echocardiographic assessment of cardiac function has based on 2D echocardiography and Doppler interrogation on intracardiac blood flow. Spectacular progresses in ultrasound imaging have made possible the direct evaluation of myocardial motion and deformation in real time. In 1972, Kostis et al first described pulsed wave Doppler method for posterior wall velocities (5). However, Isaaz et al first introduced the concept of tissue Doppler echocardiography to evaluate the myocardial velocities (6), and the use of colour tissue Doppler echocardiography was subsequently reported by Sutherland et al and Yamazaki et al (7,8). Heimdal et al formulated real time strain rate in the longitudinal axis in 1998 (9). In present, the most modern ultrasound machine are ecquiped with tissue Doppler software, which can be used during a routine echocardiographic exam. The general term „Tissue Doppler Imaging“ comprises all the quantitative parameters used for assessment of global and regional cardiac function based on tissue Doppler principle – myocardial velocities and displacement, strain and strain rate, tissue tracking and tissue shynchonization imaging.

Technical principle of tissue Doppler

Tissue Doppler principle is based on the difference between signals returned from blood and tissue. Unlike the blood flow Doppler signals, which are characterized by high velocities and low amplitude, Doppler signals from the myocardial wall have low velocities (up to 10-15 cm/s in healthy individuals) with high amplitude (7,8). This technique filters out the high velocity, low amplitude signals, leaving the
tissue motion information visible. During image acquisition, it is important to optimise the frame rate (90-250 frame per second) using an image sector as narrow is possible and to correct the angle alignment of the ultrasound beam, similar to the blood flow Doppler recordings.

**Modalities of Tissue Doppler Imaging**

There are 3 modalities of recordings of tissue Doppler imaging: 2D colour Doppler, M-mode colour Doppler, and spectral pulsed wave Doppler.

**2D colour Doppler** of the myocardium allows us to superimpose wall motion velocity on the two-dimensional echocardiographic imaging, by velocity color coding. Depending on the orientation of the cardiac structures relative to the ultrasound beam, the velocity signals appear red or blue according to movement of the myocardium towards or away from the transducer, respectively (figure 3). In the same time, 2D colour Doppler temporal and spatial resolution are dependent on frame rate (it must be at least 90 FRS), which is related to probe frequency and sector angle. If at the beginning of tissue Doppler era, the colour coded images were visually analyzed using only color velocities scale, now tissue Doppler images can be obtained real-time and velocity curves may be analyzed later by postprocessing. Peak and mean velocities (measured in cm/s), and regional time intervals (measured in milliseconds) – can be measured in each myocardial segment and in each phase of the cardiac cycle (figure 3 and figure 4).

**M-mode colour** has a high temporal and spatial resolution, thus myocardial gradients between epi- and endocardium may be obtained.

**Pulsed Wave Tissue Doppler imaging** measures online myocardial velocities and time intervals with an excellent temporal resolution. On contrary, spatial resolution is poor, since the ventricular wall moves whereas the sample volume is fixed, and myocardial layers can not be separately be analyzed (10). According to the Doppler principle, tissue velocities moving toward the transducer are positive and those moving away from the transducer are negative (11).

**Quantification tools for tissue Doppler imaging**

There are 7 tissue Doppler quantification tools currently available: myocardial motion –

**FIGURE 3.** 2D Colour Doppler in 4C apical view – in red wall motion towards the transducer, in blue wall motion away from the transducer -, and the off-line postprocessing analysis of the myocardial velocity curves. The sample volume is positioned in the basal lateral wall. The initial positive excursion is isovolumic contraction phase (ICT) followed by systole (S). The negative waves represent early (E’) and late (A’) diastole.

**FIGURE 4.** Timing of cardiac cycle on tissue Doppler imaging – velocities, strain, and strain rate waveforms of a normal subject from an apical 4C view. The sample volume is located in the mid interventricular septum. The tissue Doppler velocities consist from a first positive wave (ICT), a systolic wave (S), followed by isovolumetric relaxation wave (IVRT) and by the outward wall motions E’ and A’ related to ventricular filling. Longitudinal strain and strain rate profile is obtained from the same region of interest and shows corresponding waves (negative in systole, indicates longitudinal myocardial compression, and positive in diastole, indicates longitudinal expansion). Modified from 11.
NEW ECHOCARDIOGRAPHIC TECHNIQUES FOR THE ASSESSMENT OF CARDIAC FUNCTION

velocities and displacement; curved M-mode colour display; myocardial velocity gradient; myocardial deformation – strain, and strain rate, myocardial synchronicity – tissue synchronisation imaging.

**Myocardial velocities (cm/s).** A normal waveforms of myocardial velocities are illustrated in figure 4. As we already showed, simultaneous Doppler interrogation of multiple myocardial segments can be obtained off-line, using high frame rate colour Doppler recordings. Velocities measured off-line are lower that those obtained from online pulsed Doppler (with about 25%). Basal interventricular septum and posterior wall from parasternal long axis view reflect the radial motion of the left ventricle. Mitral annular and basal left ventricular, and tricuspid annular velocities reflect the long-axis motion of the left and right ventricle, respectively (12). It has been demonstrated that longitudinal velocities increase from apex to base. This means that motion in the base is an effect of apical contraction – tethering effect. Thus, tissue Doppler velocities are criticable in accurate evaluation of myocardial ischemia, because passive segments can show motion, without deformation due to tethering effect.

Peak myocardial systolic velocity averaged from 6 sites of the left ventricular mitral annulus correlates well with left ventricular ejection fraction, and a cut-off > 7.5 cm/s had a sensitivity of 79% and specificity of 88% in predicting normal global left ventricular function (13). Furthermore, several studies showed that diastolic tissue Doppler waveforms (E’ and A’, E’/A’ ratio and E/E’ ratio) represent a good predictor for cardiac outcome (14). Tissue Doppler velocities have been validated using a ventriculography or a rotating sponge model (15), and a correlation between time intervals assessed by tissue Doppler imaging and those assessed haemodynamically has been demonstrated (16). Regarding the method reproducibility, it has been reported a interobserver reproducibilities for peak systolic velocity from 4% for lateral mitral annulus to 24% for short-axis (17). Katz et al reported a good interobserver variability of 3.8±16.5% for color coded tissue Doppler imaging (18). Moreover, tissue Doppler velocities are related to the interstitial fibrosis level and to the myocardial beta-adrenergic receptor density (19). There are described several limitations of the myocardial velocity assessment using tissue Doppler imaging. First, there are angle dependence and an high frame rate recordings. Second, tethering effects in scar regions may limit accuracy by “false” normal velocity of dysfunctional segments. Finally, although Doppler signals are less influenced by poor image quality, tissue Doppler analysis is impossible where there is no delineation between myocardium and surrounding structures.

**Myocardial displacement (mm)** is defined as a velocity time integral of the curves in systole or diastole. This parameter can be measured using another tool of tissue Doppler imaging – tissue tracking. Tissue tracking allows the visualization of longitudinal motion in each myocardial segment during the cardiac cycle, by colour coded scale. Furthermore, this method permits off-line measurement of myocardial displacement, showing that basal interventricular septum has higher systolic and diastolic displacement than the apex (figure 5).

**Curved M-mode colour display** is a reconstructed colour M-mode record along a manually traced line, that allows a visual display of segmental asynchrony between myocardial segments (figure 6). Thus, regional delay can be measured according to temporal resolution.

**Myocardial velocity gradient (s⁻¹),** between endocardium and epicardium (figure 7) reflects the rate of changes in wall thickness. Systolic myocardial velocity gradient is a indicator of regional function, that is little affected by the Doppler angle of incidence.

FIGURE 5. Myocardial displacement (mm) assessed from tissue tracking imaging – high motion of the basal interventricular septum and lower at the left ventricular apex.
FIGURE 6. Curved M-mode colour display at tissue Doppler imaging – transseptal synchrony during cardiac cycle in a healthy subject.

FIGURE 7. Myocardial velocity gradient (s⁻¹) in a normal healthy subject.
Strain and strain rate. As the consequences of limitations of velocity assessment, described earlier, strain rate imaging was introduced in 1997. Strain (%) is defined as tissue deformation – compression distention of myocardial segments. According to the equation $S=\Delta l/l_0$, where $S =$ strain, $\Delta l =$ change of length, and $l_0 =$ basal length, expansion of the myocardium is positive strain (normal longitudinal diastolic strain), whereas shortening is negative strain (normal longitudinal systolic strain). Strain rate $(s^{-1})$ measures the rate of deformation of the myocardial segments, which is equivalent with myocardial velocity gradient. We can assessed regional strain rate by colour coded method, such as curved M-mode, as shown in figure 8. The technique of data storage and postprocessing permits the measurements of peak systolic strain and strain rate, and peak early and late diastolic strain rate from the same sample volume within the same cardiac cycle (figure 4). The normal value for a longitudinal systolic strain is 15-25% and of a radial strain, and for longitudinal systolic strain rate 1-1.4 $s^{-1}$. Post systolic movement identified with velocity or displacement, can be differentiate using strain, into passive or active motion. If there is a contraction after the aortic valve closure, this is defined as a post systolic shortening and represents a marker of myocardial asynchrony, myocardial ischemia and/or viability of severe hypo/akinetic segments (20).

Tissue synchronization imaging is a new echocardiographic technique that used color-coded time-to peak tissue Doppler velocity (the interval from the beginning of QRS complex to the beginning of systolic wave). Thus, it can identify dissynchronic segments in real time by superimposing these temporal motion data to the 2D echo images. The color coding is green (for normal time to peak velocity 20-150 ms), yellow (150-300 ms) and red ( > 300 ms). Recently, have been developed a technique that allows multiplane examination in 3 dimension of the left ventricle (figure 9), and permits the measurements of asynchrony indexes from 6 myocardial segments, such as standard deviation of time-to peak (pathological over 32 ms).

Clinical application of tissue Doppler imaging

Numerous clinical and experimental studies demonstrated the clinical utility and application of tissue Doppler imaging: assessment of systolic...
and diastolic left and right ventricular function; coronary artery disease, including stress echocardiography, cardiac resynchronization therapy, cardiomyopathy.

**Assessment of systolic and diastolic left and right ventricular function**

As we already mentioned, mitral annular systolic velocity can be used as an index of global ventricular function (13, 21). Mitral annular peak systolic velocity is also a sensitive marker of slightly impaired left ventricular systolic function, even if EF is preserved, such as "diastolic heart failure" (22), or in diabet subjects, with or without overt cardiovascular disease (23). This parameter is a strong predictor for outcome in several condition. Wang et al showed that cardiac mortality was significantly higher when both systolic peak and early diastolic peak were <3 cm/s (HRs 7.5 and 5.3 respectively), in a cohort of 518 subjects (353 with cardiac disease and the rest normal) (14). Moreover, Agricola et al, in a study published in 2004 showed that tissue Doppler on the lateral mitral annulus systolic velocity could predict those who would develop reduction in ejection fraction after mitral valve surgery (24).

In the same time, decreased E’ is one of the earliest marker of ventricular dysfunction. In restrictive pattern, because the E’ velocity is reduced and E velocity increases with left ventricular filling pressure, the E/E’ ratio is strongly related with left ventricular filling pressure and pulmonary capillary wedge pressure (PCWP) (25). It has been well established that PCWP is > 20 mm HG, if E/E’ is > 15 and normal if E/E’ is< 8. Moreover, this index is a very powerful prognostic marker, in a study of 182 patients with left ventricular systolic dysfunction, E/E’ > 15 was found in a 97% of a deceased subjects after a 48 follow-up period (26).

Tricuspid annular velocity can be used as an index of right ventricular function in patients with cardiac failure. A systolic annular velocity < 11.5 cm/s predicted right ventricular ejection fraction < 45 % with a sensitivity of 90% and a specificity of 85% (27).

In the last 10 years, real time strain and strain rate has become a very important tool in order to assess myocardial function. Unlike tissue velocity measurements, deformation assessment is specific for the region of interest, and therefore is not influenced by the tethering effect. Strain and strain rate have been used for evaluate subclinical ventricular dyfunction in a diseases like hypertension, diabetes, Fabry disease, infiltrative disorders (11). And, indeed, reduction of strain and strain rate has been correlated with myocardial fibrosis (28). Although the prognostic value of strain and strain rate are not well defined yet, it seems...
likely that increase in myocardial deformation would be associated with outcome improvement.

**Coronary artery disease**

Longitudinal myocardial fibres are primary affected in an ischemic event. During acute coronary occlusion, peak systolic velocity decrease, a reversal of isovolumetric relaxation velocity and reduction of early and late diastole velocities can also be observed. Post systolic shortening or thickening is an important marker of ischemia and can be identified by high velocity, strain and strain rate, that often exceeding into the filling phase (29). However, post systolic shortenning is a normal finding in healthy subjects occuring in about a third of myocardial segments, and, therefore it is not always a marker of disease. Pathological post systolic shortenning has an high amplitude, with coexisting reduction in systolic strain and strain rate, and its peak is later than in normal subjects (30). It has been demonstrated that strain and strain rate are more sensitive technique than tissue Doppler velocity for detecting regional ischemic wall motion abnormalities during acute ischemia. However, ischemia and stunning can be distinguish using a dobutamine infusion (31). In case of ischemia, strain and strain rate will decrease, with appearance of post systolic shortenning, in contrast with stunning. Myocardial strain rate can also differentiate between acute and chronic ischemia (32). Infarcted myocardium is carachterized by significantly decrease of systolic and diastolic velocities, and of myocardial deformation, and by the loss of homogenous distribution of strain from apical to basal segments.

Katz et al, found significantly lower systolic velocities at peak stress in abnormal than in normal ventricular wall during stress echocardiography (18). Furtheremore, viability assessment of stress echocardiography in combination with tissue Doppler imaging showed results comparable with thalium-201 tomography (33).

**Cardiomyopathy**

Several studies demonstrated that tissue Doppler velocities, strain and strain rate can detect subclinical dysfunction in patients with cardiomyopathy. In hypertrophic cardiomyopathy, tissue Doppler imaging detected myocardial contraction and relaxation abnormalities – mitral annular systolic velocity < 12 cm/s and early diastolic velocity < 13 cm/s, having a sensitivity of 100% and a specificity of 90%. (35). Furtheremore, the best differentiation between physiological and pathological hypertrophy was provided by a mean systolic annular velocity < 9 cm/s (sensitivity 87%, specificity 97%) (36). In restrictive cardiomyopathy, mitral annular velocity and posterior myocardial velocity gradient were reduced, whereas these parameters were within normal range in constrictive pericarditis (37).

**III. SPECKLE TRACKING ECHOCARDIOGRAPHY**

Speckle tracking echocardiography is a new ultrasound technique that allows evaluation of ventricular global and regional function, offering the advantages to track myocardial deformation independently of both cardiac translational insonation angle. The method is based on the scattering, reflection and interference of the ultrasound beam in myocardial tissue – speckles. These speckles represent tissue markers that can be tracked from frame to frame through entire cardiac cycle.

By analysing a speckle motion, speckle tracking echocardiography permits to assess myocardial tissue velocity, strain and strain rate...
and torsion of the ventricle, independently of cardiac translation and angle beam. This method allows to examine several components or plane (longitudinal, radial and circumferential) in a single data set. Recently, speckle tracking echocardiography was used to evaluate a new systolic indices, particularly longitudinal strain, which was shown to be a specific index in post myocardial infarct. Speckle tracking echocardiography offers the unique opportunity to assess torsional deformation of the left ventricle (figure 10). Estimated of left ventricular torsion and twisting velocities measured by speckle tracking echocardiography in patients with or without cardiomyopathy are well correlated to those measured by cardiac magnetic resonance. Another potential clinical application of speckle tracking echocardiography is quantification of LV dyssynchrony, in order to increase the rate of responder to the CRT (figure 11).

**IV. 3D AND 4D ECHOCARDIOGRAPHY**

On the last decade, significant developments in 3D and 4D (real time and color echocardiography) have been made. Numerous applications of 3D and 4D echocardiography have been proposed, like an important value in surgical decision in valvular pathology or in complex cardiac diagnosis. In addition, 3D and 4D imaging allows quantitative parameters such as accurate valve geometry and cavity dimensions (figure 12, the size of the cardiac defects, or assessment of cardiac volumes. Recently, it has been developed a real time 3D reconstruction and measurement of ejection fraction (figure 13).
NEW ECHOCARDIOGRAPHIC TECHNIQUES FOR THE ASSESSMENT OF CARDIAC FUNCTION

FIGURE 12. Speckle tracking imaging and dyssynchronism evaluation. Apical chamber view shows complete dyssynchrony of different segments of interest assessed as longitudinal systolic strain.

FIGURE 13. Real time 3D left ventricular reconstruction.

In conclusion, new echocardiographic methods, such as tissue Doppler imaging, speckle tracking imaging and 3D/4D echocardiography are simple, easy methods with an important potential of becoming the reference clinical tools for the evaluation of cardiac function – motion and deformation.
REFERENCES


25. Sohn DW, Chai IH, Lee DJ, et al – Assessment of mitral annulus velocity by tissue Doppler imaging in the the evaluation of left ventricular diastolic function. J Am Coll Cardiol 1997; 30:474-480


34. Bax JJ, Abraham T, Barold SS, et al – Left ventricular dysynchrony predicts response and prognosis after...
heart resynchronization therapy. J Am Coll Cardiol 2004; 44:1834-1840

