REVIEW

WHAT ADDITIONAL INFORMATION CAN PROVIDE DOPPLER MYOCARDIAL IMAGING FOR DAILY CLINICAL PRACTICE?

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**Summary**

The present review is designed to demonstrate some most practical and widely recognized areas of clinical Doppler myocardial imaging (DMI) application. The history and principles of the method are briefly described. In order to understand the potential of myocardial velocity imaging, the relationship between myocardial architecture and function is covered. The attention is focused on possibilities of DMI to diagnose and monitor myocardial ischemia and evaluate global and regional diastolic function. Other applications of DMI in daily practice and perspectives of the method are reviewed as well.

**Current limitations of conventional echocardiography**

The non-invasive evaluation of myocardial function is a key task in the management of patients with heart diseases. In daily practice, echocardiography is a widely accepted method to estimate global contractility of the left and right ventricles and identify segmental asynergy.

However, sometimes practitioners can feel that conventional grey-scale echocardiography does not provide sufficient information about global and regional myocardial function. For example, how to evaluate cases when two independent observers do not agree on interpreting myocardial contractility? How relevant is the Simpson's method of ejection fraction (EF) calculation based on endocardial visualization? What events do we probably miss during transient ischemia when assessing myocardial wall motion only visually? These and other questions frequently rise in daily practice.

Inter-observer variability is a well-known problem in cardiology, and almost all diagnostic methods have been examined for inter-observer and intra-observer agreement. Widely used conventional echocardiographic techniques are highly dependent on image quality and endocardial definition, therefore they are inherently subjective and poorly reproducible. Shortcomings of visual assessment of myocardial thickening have been notably demonstrated in stress echocardiography practice. In 1996 Hoffmann et al. [1] published data of low inter-institutional observer agreement in the interpretation of dobutamine stress echocardiograms (DSE). In 2002, after the implementation of second harmonic imaging, side-by-side digital display and standardized reading guidelines, the same research group explored a degree of inter-institutional agreement in the assessment of dobutamine stress echocardiograms [2]. In spite of improvements in reader agreement on interpretation, a significant variance between centres was still found. To large extent, it can be explained by recent studies, which have shown physiological limitations of a human eye to resolve a rapid, short-lived motion [3].

Marwick and other authors propose that the development of a quantitative approach could overcome limitations of subjective evaluation of DSE images [4]. If a particular threshold of wall motion or velocity could be identified, there would be a little opportunity for variation in interpretation between reviewers [4]. The increasing demand for objective, quantitative evaluation of global and regional myocardial function stimulates the integration of a relatively new method of Doppler myocardial imaging (DMI) into clinical echocardiography. Myocardial tissue velocity imaging has been performed for more than 10 years. From being mostly a subject of continuous technical refinement and a tool in various research activities, it is now becoming a valuable complement to routine echocardiographic evaluation [5].

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The present review is designed to demonstrate some most practical and widely recognized areas of clinical DMI application.

**Principles of Doppler myocardial imaging**

DMI allows the quantification of low intensity, high amplitude Doppler shifts in a range of myocardial tissue motion. Pulsed-wave and colour Doppler myocardial imaging technique can quantify both regional myocardial motion (i.e., velocity and displacement) and deformation (i.e., strain rate and strain) [6]. Regional myocardial systolic and diastolic function can be characterized by measuring one or more of the following parameters: the timing of regional events, regional myocardial thickening and thinning, the velocity and direction of regional myocardial motion [7].

The use of Doppler ultrasound to record wall motion was initially reported some 40 years ago [8]. Then, in 1989 Isaaz [9] reported the use of DMI in the evaluation of the left ventricular (LV) function with pulsed Doppler recordings of intra-myocardial velocities in the posterior wall both in normal subjects and in patients with regional function abnormalities. The use of colour DMI, including M-mode and two-dimensional (2D) instrumentation, was subsequently reported by Sutherland et al [6]. In vitro studies with tissue-mimicking phantoms have validated the accuracy of this method for velocity measurement [10].

First, the report of normal pulsed-wave Doppler velocity curves and peak velocity values at different sites around the mitral annulus was published [9]. Then normal velocity values for systolic and diastolic motion of myocardial walls have been estimated [11–14]. Concomitantly, a longitudinal trans-myocardial velocity gradient as well as age-dependent variability of diastolic velocities has been described [11]. Each of these studies has reported regional differences in the myocardial segments analyzed: systolic velocity recorded at the base is greater than that in the mid left ventricle or the apex. Longitudinal and radial velocities exhibit specific normal ranges based on the location within the ventricle, what must be taken into account in any clinical application [15,16]. In general, values greater than 9 cm/s in basal segments are considered normal (Table 1).

As Doppler velocity estimation is based on the measurement of phase shift rather than signal strength, the technique is relatively independent of chest wall attenuation [6]. Thus, it is possible to obtain DMI curves of diagnostic quality even from patients who are considered poorly echogenic on standard two-dimensional echocardiography.

Spectral (or pulsed) Doppler interrogation of the myocardium is the most widely used in the clinical setting because of its easy quantitative on/off-line analysis [10]. With this modality, a sample volume is placed within the myocardium (Figure 1). The spectral pulsed-wave (PW) Doppler method provides the highest temporal resolution (8 ms) and resolves all peak velocities (Figures 2, 3).

In colour DMI modality all the points within the ventricular walls are velocities encoded in real time.

**Table 1.** Normal values ± SD in cm/s for the basal segments of the left ventricle using pulsed DMI [11–16] (reproduced with permission [16])

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>E'</th>
<th>A</th>
<th>E′/A′ ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral</td>
<td>10.6±2.3</td>
<td>13.3±3.3</td>
<td>11.3±2.9</td>
<td>1.5±0.6</td>
</tr>
<tr>
<td>Septal</td>
<td>9.9±1.7</td>
<td>11.5±2.6</td>
<td>9.5±2.4</td>
<td>1.0±0.7</td>
</tr>
<tr>
<td>Anterior</td>
<td>9.2±1.8</td>
<td>11.7±3.4</td>
<td>10.3±2.9</td>
<td>1.2±0.7</td>
</tr>
<tr>
<td>Posterior</td>
<td>10.4±2.5</td>
<td>14.3±3.6</td>
<td>11.6±2.6</td>
<td>1.3±0.7</td>
</tr>
</tbody>
</table>

S′ – peak systolic myocardial velocity; E′ – peak early diastolic myocardial velocity; A′ – peak late diastolic myocardial velocity

![Figure 1. The interrogation of myocardial segments with pulsed-wave DMI modality. Note the location of the sample volume within the myocardial wall. LV – left ventricle; RV – right ventricle; LA – left atrium, Ao – aorta](image1.png)
Figure 2. Time relationship between the spectrum of myocardial velocity (top) and blood flow velocity recording (bottom). AC – aortic valve closure; AO – aortic valve opening; MO – mitral valve opening; E – early diastolic wave of mitral inflow; A – late diastolic wave of mitral inflow; E’ – early diastolic myocardial velocity; A’ – late diastolic myocardial velocity; S – systolic myocardial velocity; AoEj – wave of aortic ejection

Figure 3. Six consequent phases of the cardiac cycle in the myocardial velocity spectrum: (1) isovolumic contraction: positive wave of short duration; (2) systole: positive wave of myocardial contraction; (3) isovolumic relaxation: biphasic wave – ventricular reshaping; (4) early diastolic filling: negative wave; (5) diastasis: no motion; (6) atrial filling: second negative wave
Depending on the orientation of the cardiac structures relative to the ultrasound beam, the velocity signals appear red or blue according to the movements of the myocardium towards or away from the transducer, respectively. Moreover, different colour-coding scales reflect different velocities: low velocities are coded with dark colours and high velocities with bright colours [7,10]. The colour-coded Doppler tissue images are superimposed on conventional two-dimensional black and white ultrasound images. Thus, regional myocardial velocities can be recorded both with colour and pulsed Doppler, with colour Doppler measuring mean velocities and pulsed-wave Doppler resolving peak velocities. The mean velocities are generally about 15–20% lower than those obtained by pulsed Doppler [7].

The translation of the whole heart also affects the measurement of actual wall velocities. However, regional myocardial velocities represent the net effect of the contractile and elastic properties of the area under investigation and traction and tethering effects from other regions. In addition, the translation of the whole heart influences the measured velocities [17]. Recently, the concept of myocardial strain has been applied to DMI [17,18]. Strain means the deformation of a tissue segment over time. The rate of this deformation, called strain rate, is equivalent to the local myocardial velocity gradient in either the radial or longitudinal direction. The strain rate is estimated by the myocardial velocity gradient between two points normalized by the computation area (empirically kept constant at 10 mm for all the studies) (Figure 4) [17]. Though derived from myocardial Doppler velocity data, it allows the calculation of 1-dimensional regional myocardial deformation, which is independent of the influences of global heart motion or the motion of neighbouring myocardial segments.

By convention, negative strain represents regional shortening, and positive strain-lengthening. Strain, obtained by integrating strain rate over time, represents percentage change in shortening/lengthening. It has been shown to compare well to regional strain estimations obtained in open-pericardium animal models using ultrasonic crystals [19]. Strain correlates well with LV stroke volume, while strain rate correlates with LV $dP/dt$. Despite theoretical attraction and an extensive publication record, today strain/strain rate imaging remains a research rather than a clinical tool. The predominant reasons for this relate to technical problems compromising signal quality and the need of post-processing, which is often sophisticated and time-consuming.

**Myocardial architecture**

The origin of DMI velocities is related to the myocardial architecture and fibre orientation [16]. A man of genius Leonardo da Vinci far back wrote that a cardiac ventricle shortened during systole and lengthened during diastole [20]. Then Grant [21] described the myocardial architecture as a syncytium of interconnected myocardial fibres. Epicardial fibres twist in a clockwise, helical orientation from the base to the apex, whereas endocardial fibres twist in a counter-clockwise manner (Figure 5). The apex is relatively stationary and composed of a very thin myocardial fibre layer. Rushmer et al [22] reported that myocardial fibres located in the subendocardial and epicardial layers are longitudinally oriented. Tension develops first in the longitudinal fibres during initial ventricular activation; then long-axis contraction occurs before it happens in the mid-myocardial, circumferentially oriented fibres. The further work by Greenbaum et al [23] showed that myocardial fibres were more often circumferentially oriented closer to the base of a heart. The coupling of these fibres is most complex in the basal region of the ventricles, particularly in the septum.

Standard 2D echocardiography emphasizes a visual assessment of regional myocardial thickening and therefore provides the evaluation of radial function only. However, the longitudinal function of the left ventricle is important. It is the motion of the atrio-ventricular plane towards the fixed apex act-
The longitudinal myocardial function can be evaluated when DMI parameters are measured from the apical views. Numerous reports demonstrate the importance of longitudinal myocardial function, especially in the diagnosis of ischemic heart disease [7,9,10,16]. It has been suggested that when subendocardial ischemia occurs, impaired long-axis shortening is evident before changes in short-axis shortening because of the myocardial fibre orientation [16]. Recently, the impairment of longitudinal myocardial function has been shown in patients with essential hypertension and normal ejection fraction [25]. Hypertensive patients, who previously were considered having isolated diastolic dysfunction, were demonstrated to have a reduced LV systolic longitudinal function.

**Diagnosis of myocardial ischemia**

Experimental sonomicrometric techniques have defined the actual sequence of regional changes in myocardial function induced by acute ischemia [26–28]. These include a delay in the onset of contraction, a progressive decrease in the rate and degree of thickening, and a progressive delay in the time of peak thickening until this event occurs in what is early diastole for the surrounding non-ischemic myocardial segments. Finally, with total occlusion, systolic thickening is virtually or completely abolished and only late systolic/early diastolic thinning occurs. In parallel with the incremental decrease in systolic thickening the second event occurs, the development of increasing post-systolic thickening (Figure 6).

The fundamental experiment of Leone et al [26] has shown that the shift of shortening from the systolic to the post-systolic phase is the earliest functional abnormality of mild myocardial ischemia, and as the severity of ischemia progresses, post-systolic shortening increases in magnitude as the magnitude of systolic shortening decreases. The decrease in systolic thickening with the concomitant increase in the degree of post-systolic thickening has been shown to enhance not only with the degree of ischemia, but is also potentiated by an increase in load [26].

Routine angioplasty is often used as a clinical model of acute ischemia [29]. In an early study by Bach et al [30], DMI was estimated as a sensitive indicator of myocardial dysfunction. All typical regional changes in ischemic myocardium can be detected and measured by DMI method, using either velocity or strain rate imaging. Therefore, DMI can be used in the detection and monitoring of myocardial ischemia during acute coronary syndromes as well as in stable angina. When the technique of DMI was applied simultaneously with coronary angioplasty [30], prior to conventional signs of ischemia a decrease in myocardial tissue velocities was observed. During artery occlusion, radial and longitudinal strain in appropriate myocardial segments decreased by nearly 50% compared with baseline values [29]. At the same time, post-systolic deformation increased. In the presence of chronic myocardial infarction, normal myocardial velocities induced by contraction and relaxation may be absent in a scar segment [7]. In patients with the infarction, clear regional changes in strain rate have been shown to occur when compared to the more uniform distribution of this parameter in normal subjects [19].
Several further reports revealed that visually normal myocardial segments could demonstrate the abnormal pattern of regional velocities. The systolic strain rate and strain were significantly altered in normokinetic segments supplied by a stenosed coronary artery [31]. A prolongation of isovolumetric relaxation time and a decrease in the early diastolic velocity has been described in ischemic myocardial segments [29]. The typical ischemic curve of myocardial velocity can be very helpful in daily practice, when present or previous myocardial infarction (MI) has to be confirmed by echocardiography.

Many investigators have incorporated DMI in the protocol of stress echocardiograms. In a number of clinical studies the peak velocities in systole and diastole were found significantly lower under dobutamine stress in the mal-perfused myocardial region than in the reference wall [32–34]. Several authors [35,36] have concluded that myocardial velocity gradient can detect ischemia, even at submaximal dobutamine dosages, and is superior to standard 2D methods of wall motion analysis. Marwick et al [37] have shown the improvement in the concordance of DSE interpretation using DMI compared to visual evaluation of wall motion score.

Several diagnostic criteria for the detection of induced ischemia were suggested. Yamada et al [32] reported the use of DMI during dobutamine stress echocardiography. Myocardial segments with ischemia had a systolic velocity <12 cm/s at peak dobutamine dose, with 83% sensitivity and 87% specificity. A lack of increase in systolic velocity after an exercise was reported to be a sensitive indicator of ischemia in the studies by Pasquet and colleagues using dual-isotope single-photon emission computed tomography [38]. Insufficient growth of systolic velocities in ischemic myocardial segments during dobutamine echocardiography was confirmed in our recent research [39] and site-specific cut-off values for detecting ischemia were suggested.

So far, the evaluation of regional diastolic wall motion has not been possible with semi-quantitative stress echocardiography, due to its low frame rate with respect to the short duration of early diastolic events. The quantification of diastolic myocardial function by pulsed Doppler myocardial mapping during dobutamine stress was shown as a feasible, accurate, and reproducible technique [40]. It has been proposed as a sensitive alternative to the present echocardiographic and scintigraphic imaging techniques for stress tests. Stress induced reduction of E’ wave by 2 cm/s discerned the best diagnostic accuracy (sensitivity 84%, specificity 93%) in comparison with two-dimensional echocardiography (78% and 71%) and perfusion scintigraphy (61% and 86%). In parallel, other authors have concluded that diastolic LV abnormalities are sensitive early signs of myocardial ischemia and have the additional advantage of persisting longer than systolic disturbances [41].

Our research using DMI during DSE demonstrated that the most sensitive index of induced ischemia was the velocity of post-systolic motion (PSM) [39], providing the high sensitivity and reasonable specificity in diagnosing coronary stenosis. Similarly, recent report using strain/strain rate imaging during dobutamine echocardiography revealed the superior sensitivity of the index of post-systolic deformation comparing to strain during ejection time and maximal deformation during the entire heart cycle [42]. Besides, PSM can be seen easily and fast on-line during stress echocardiography, thus allowing early suspicion of ischemic changes. However,
PSM can be a normal finding in healthy subjects, and the criteria to consider it pathological would be its absolute magnitude, the ratio between systolic and post-systolic motion and its transient character during stress [39,43].

Thus, it seems that an accurate quantification of regional longitudinal function changes during acute ischemia requires the combined analysis of regional systolic and diastolic as well as post-systolic thickening abnormalities. The complex of site-specific cut-off values of systolic, diastolic and post-systolic velocity has been suggested [39].

The differential placement of the longitudinal fibres in the subendocardium may render longitudinal velocity uniquely sensitive to mild or early ischemia during stress [44]. Studies during dobutamine echocardiography support the hypothesis that myocardial velocity determined by DMI reflects myocardial contractility, and the catecholamine-induced alteration in contractility is better reflected by changes in myocardial velocity than by changes in ejection fraction [45,46].

Global and regional diastolic function

Perhaps, the most popular application of DMI is the estimation of pseudonormal pattern of diastolic dysfunction of the LV. It is widely recognized that about 35% of patients with congestive heart failure (CHF) have preserved systolic LV function. Therefore, a differentiation between normal and pseudonormal diastolic function in this subset of patients is crucial in daily practice. Echocardiographic indices of global diastolic function are used to evaluate a complex interaction between the active process of relaxation, the elastic properties of the myocardium, and instantaneous atrial and ventricular pressures.

The evaluation of global LV diastolic function by the pattern of transmural flow velocity is limited because transmural flow demonstrates a pseudonormalization pattern in patients with a markedly elevated LV end-diastolic pressure [47]. Load dependency of the mitral inflow parameters has been well recognized. Increased driving pressure at the mitral valve opening increases the E velocity and shortens deceleration time. Early diastolic DMI parameters obtained from the LV posterior wall have been shown to correlate closely with the time constant for the LV pressure decay during isovolumic diastole (τ), a load-independent measure of relaxation. It has been determined by cardiac catheterization, even in patients with a markedly elevated LV end-diastolic pressure [48].

With changes in volume status, changes in annular or myocardial velocities have been noted to be less than the corresponding changes in mitral flow velocities [7]. However, the recent studies have shown that the influence of volume changes on wall velocities is not negligible [7].

Rodriguez and colleagues [47] reported that patients with LV hypertrophy have a reduced E′ compared with that of healthy controls, despite the lack of differences in conventional mitral Doppler indexes. Similarly, early diastolic wave of mitral annulus helps to differentiate physiologic LV hypertrophy from pathologic one. Therefore, pulsed DMI provides a superior method for the identification of patients with impaired LV relaxation, regardless of the mitral inflow pattern (restrictive, pseudonormal, or impaired relaxation) measured by conventional pulsed Doppler. Sohn et al [49] demonstrated that E′ was an accurate measure of abnormal LV diastolic function, despite the presence of atrial fibrillation. The threshold value of E′ used to identify diastolic dysfunction should be approximately 8 cm/s.

Peak early diastolic mitral flow velocity E increases with increasing pulmonary capillary wedge pressure (PCWP). In contrast, E′ remains decreased in this stage of diastolic dysfunction (Figure 7). The ratio between flow velocity and annular velocity have been shown to provide a useful estimate of PCWP, even in the presence of sinus tachycardia, left ventricular hypertrophy or atrial fibrillation [48]. Nagueh et al [48] demonstrated that the ratio E/E′ > 10 was associated with PCWP > 12 mmHg (sensitivity 91%, specificity 81%). An equation for the calculation of PCWP was suggested:

PCWP = 1.24(E/E′) + 1.9.

The ratio E/E′ has been proposed as a marker for the diagnosis of congestive heart failure and compared to B-type natriuretic peptide (BNP) [50]. Authors have concluded that DMI and BNP have similar sensitivity for diagnosing CHF, but DMI appears to be more specific.

The effect of abnormal relaxation on the early diastolic velocities can also be seen in the right ventricle (RV). In the presence of pulmonary hypertension the early diastolic myocardial velocity in the RV is reduced most probably as a result of abnormal relaxation in the hypertrophied RV [51].

Evaluation of ventricular synchronicity

QRS prolongation in the left bundle branch block (LBBB) is associated with asynchronous ventricular contraction and a depressed ejection fraction and is inversely correlated to global contractile function. Cardiac resynchronization therapy (CRT) has been recently introduced as a complementary treatment for patients with heart failure and ventricular conduction delay [52]. In patients with heart failure, biventricular pacing improves the left ventricular performance by counteracting LV unsynchronized contraction caused by the presence of LBBB [53]. Despite the promising results of CRT on both acute hemodynamic performance and long-term functional status, the selection of suitable patients still has to
be defined. There is an increasing consensus that electrocardiographical screening of ventricular dysynchrony based on wide QRS is neither adequate nor specific in identifying patients that may be appropriate candidates for CRT. Echocardiography appears to be the most promising technique for patient selection.

DMI is useful in assessing the severity of LV asynchrony in patients with LBBB and heart failure as well as in evaluating the pacing effects on long-axis function in these patients [54]. Biventricular pacing could provide additional benefit when it is applied at the most delayed site. Thus, DMI can be used to predict a hemodynamic contractile function benefit from CRT [55]. Ventricular conduction delay, as measured by the QRS duration, only weakly predicts the expected hemodynamic benefit with CRT. The maximal effect of resynchronization depends on an optimal AV delay, which impacts LV filling time [56]. The evaluation of myocardial velocities, either in pulsed or colour mode, allows to quantify the degree of ventricular dysynchrony by measuring the time from the beginning of the QRS complex till the onset of myocardial wall motion. Proposed cut-off value for LV intraventricular dysynchrony is ≥50 ms (Figure 8). The use of ultrasonic deformation parameters for the evaluation of intraventricular dysynchrony is considered more adequate as the time till true myocardial deformation in different walls of LV can be assessed.

**Other cases of Doppler myocardial imaging application**

DMI may be extremely useful in cases, when the disease of the myocardium has to be confirmed or excluded. It may be difficult to differentiate constrictive pericarditis (CP) from restrictive cardiomyopathy during clinical examination. The interrogation of atrioventricular valve plane motion by Doppler myocardial imaging has been suggested as a valuable new approach that can help to differentiate one from another. In restrictive cardiomyopathy LV systolic function is usually impaired, and reduced annular velocities may be helpful in differentiating this from constrictive pericarditis. E’ velocity is well preserved in patients with CP even when there is no significant
respiratory variation of E velocity. Thus, E’ velocity can provide a helpful diagnostic indicator for CP and should be measured routinely in the evaluation of patients with suspected CP. Preserved E’ velocity shown by DMI should support the diagnosis of CP over a primary myocardial disease [57].

Strain echocardiography has been shown as a sensitive technique in the detection of cardiac involvement in patients with primary amyloidosis despite normal wall motion and EF estimated by conventional echocardiography [58].

DMI may represent a useful tool while differentiating between athlete’s heart and hypertrophic cardiomyopathy diagnoses. It has been shown that in case of pathological LV hypertrophy systolic and diastolic velocities of LV segments are reduced comparing to physiological hypertrophy [59]. Recently, the evaluation of RV diastolic function by DMI has been reported as a valuable method discriminating the pathological LV hypertrophy from physiological one [60].

In daily practice, the assessment of RV function is challenging because of anatomic and functional complexity of this chamber. Measurements of tricuspid annular motion are easy to obtain, correlate with the Simpson’s RV EF, and have a high sensitivity and positive predictive value for detecting normal RV
systolic function (peak systolic velocity ≥ 10 cm/s) [61].

**Future perspectives**

For the latter 10 years, DMI has been proposed as a feasible and useful imaging tool that provides information on the dynamics of regional wall motion. The implementation of DMI in research and clinical practice improves our understanding of the basics of myocardial function and compensatory mechanisms.

There is growing evidence, that DMI measurements can provide not only valuable diagnostic information, but important prognostic information as well.

In patients with the first acute MI treated with primary angioplasty, DMI assessment of systolic and diastolic velocities of the mitral annulus representing infarcted segments has been shown to predict the incidence of in-hospital cardiac events and to be superior to other echocardiographic variables [62]. The ratio E/E’ has been demonstrated as a predictor of hospitalization in a community-based study of patients with symptoms of breathlessness or edema [63].

The new promising fields of DMI application include the assessment of atrial contractile function [64,65], studies of arterial wall displacement [66], the prediction of LV systolic function recovery after open heart surgery [67] and others.

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