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REVIEW PAPER

Velocity and deformation imaging for the assessment of myocardial dysfunction

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Recent developments in echocardiographic imaging technology and processing enabled the quantification of myocardial motion and deformation in a clinical setting. Echocardiographic strain (-rate) imaging provides a relatively easy way to study myocardial deformation. However, although (local) deformation is clearly linked to cardiac (dys-) function, it is important to understand how this information can be used in clinical practice and how specific deformation patterns should be interpreted. This review paper first discusses which issues are important to address when assessing cardiac function and how (regional) deformation and myocardial contractility are related. The use and interpretation of deformation profiles is further illustrated for some typical cardiac pathologies. The observed deformation patterns are discussed in light of the changes in regional contractility (ischemia), timing of contractile force development (LBBB and heart failure), pressure/volume overload, and assessing diastolic function.

Introduction

Recent developments in echocardiographic imaging technology and processing enabled the quantification of myocardial motion and deformation in a clinical setting. Echocardiographic strain (-rate) imaging [either based on Doppler myocardial imaging (DMI)[1] or speckle tracking[2]] provides a relatively easy way to study myocardial deformation.

It has been shown, both in the early animal lab work based on microcrystal measurements, and more recently using the non-invasive image based methodologies, that analysing myocardial velocities and deformation, especially when combined with the response to a dobutamine challenge, enables the assessment of myocardial dysfunction in a wide range of cardiovascular pathologies (among which: coronary artery disease and stress echo;[3–6] valvular diseases;[7,8] hypertension;[9,10] hypertrophic cardiomyopathy;[11] cardiac resynchronization therapy (CRT);[12] amyloidosis;[13] heart transplantation;[14] genetic cardiomyopathies[15,16]). One of the major strengths of quantitative deformation analysis is the discrimination of different ischaemic substrates, ranging from acute ischaemia, over stunning to chronic ischaemia with sub-endocardial fibrosis.[17]

For a proper interpretation of velocity and deformation data in a clinical setting, it is required to understand cardiac function/mechanics in normality and pathologies, combined with knowledge on how intrinsic cardiac function influences motion and deformation.

Assessing cardiac function

For the management of a broad range of heart diseases, a quantitative, reproducible approach for the assessment of cardiac (dys-) function is of great importance. However, cardiac (dys-) function is a very general and non-specific entity that is defined depending on the context. This makes it difficult to unambiguously define, and thus quantify, (dys-) function in a clinical context. Intrinsic cardiac function implies the assessment of true contractility of the myocardium. Using non-invasive approaches, this is currently not measurable and in clinical practice surrogates for true cardiac contractility are assessed and reported as reflecting cardiac function.

Figure 1 illustrates how the heart [simplified to the left ventricle (LV)] manages to fulfil its task: maintaining a

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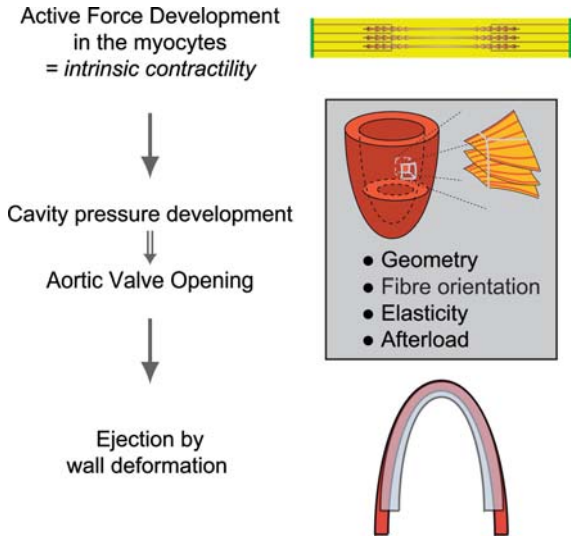

Figure 1 The functioning of the heart.

constant and adequate blood (volume) flow. The contractile elements of the myocardium can develop a contractile force and can shorten. These contractile elements are imbedded, with a very specific distribution, in the LV with a certain overall geometry (shape, thickness) and with specific elastic properties. By the initial force development of the contractile elements, the ventricle can increase its internal pressure up to the point that this is high enough to open the aortic valve. From that moment on, the shortening of the contractile elements will decrease the cavity size so that its internal blood content is ejected.

From *Figure 1*, it is clear that in order to understand the functioning of the heart, all aspects, involved in both the development of the internal pressure and the ejection of the blood by the reduction (deformation) of the cavity volume, have to be taken into account. Just measuring, for example, the ejection fraction (EF), leaves out all information on pressure, tissue properties, and the transformation from shortening of the individual contractile elements into the global deformation of the LV.

Thus, to fully describe cardiac function, two aspects and their interaction should be distinguished: force development (contractility of the myocytes, resulting in the generation of sufficient pressure to open the cardiac valves) and deformation (shortening of the myocytes, resulting in the actual volume ejection). Additionally, ventricular function can be interpreted either from a global perspective as overall pump performance, or from a regional perspective where the contributions of individual wall segments are taken into account. The interactions between the components force development and deformation are determined by the boundary conditions in which the heart functions.

These include:

- Wall properties such as tissue composition and elasticity, fiber structure, and global geometry, which determine the local segment interactions and the resulting wall stress.
- Interaction between the heart and peripheral circulation, mostly described as (pressure and volume) loading conditions.

The interpretation of cardiac function data by examining either wall mechanics (regional deformation–stress analysis) or pump performance (pressure–volume analysis) requires an integration of their measurement in the global picture of the working of the heart (*Figure 1*).

In clinical practice, this integration is usually performed in the mind of the investigator and only indirect measurements of force development and volume ejection are used to study cardiac function. These are mainly based on non-invasive imaging techniques [echocardiography, cardiac magnetic resonance imaging or computed tomography]. Usually, patients are followed clinically using echocardiography. Two-dimensional and Doppler echocardiography allow both the direct anatomical evaluation of the myocardium and the evaluation of haemodynamics. Cardiac geometry and the degree of myocardial hypertrophy can be determined by measuring ventricular size, wall thickness, and myocardial mass index.[18]

For the evaluation of (systolic) cardiac function, the intrinsic properties of the fibres and myocytes are the most important, since these determine whether the myocardium is affected by the chronic condition and their properties reflect when irreversible damage is induced. However, current evaluation is based on global indices such as EF and fractional shortening. These volume-based parameters have important limitations in reflecting contractility in the context of abnormal loading conditions because:

- The assessment of intrinsic function based on volume parameters, like fractional shortening and EF, depends on geometric assumptions. It is not well understood how these are influenced by wall thickness or ventricular shape. Often 'supra-normal' values of EF are measured in hypertrophied or volume overloaded ventricles. It is unclear whether these really reflect actual changes in contractility.[7]
- All volume-based indices are load-dependent. During disease progression, changes in loading or geometry will affect functional evaluation. For the serial assessment of myocardial contractility in such patients, an integrated approach, which takes into consideration geometry and loading, is required.
- Conventional parameters only assess global function. In most conditions, which show alterations in myocardial contractility, the assessment of regional ventricular function is important. Additionally, several of the methods for global assessment concentrate only on radial function, ignoring longitudinal function, which in most cardiac pathology is altered before changes occur in radial indices.[19] Increased radial function often acts as a compensation for the reduction in global longitudinal function.
- Global measurements do not take into account segment interactions that, e.g. only result in local wall deformation which does not contribute to pressure build up or a reduction in global ventricular volume.[20]

To overcome some of these concerns, new echocardiographic methods have been proposed to assess regional ventricular function based on myocardial motion and deformation. One of these, which has proved to be both important for understanding cardiac physiology and of clinical value is tissue Doppler imaging, which allows the quantification of myocardial velocities.[1] Post-processing techniques, based on acquired velocity data, allow the

calculation of regional myocardial deformation (strain-rate or rate of deformation and strain or amount of deformation) while post-processing of grayscale images (using speckle tracking or registration techniques) can provide information on displacement and deformation. In a lot of cardiac pathologies, the reduction in myocardial deformation correlates well with the severity of the disease.[21,22] However, it is yet unclear whether this is entirely due to a decrease in function or rather related to changes in cardiac geometry and loading.

Myocardial motion and deformation

Using either DMI (also referred to as tissue Doppler imaging or myocardial velocity imaging) or grayscale speckle tracking, motion of myocardial segments can be recorded and quantified.

Figure 2A shows the motion components that can be assessed based on echocardiographic imaging. From an apical view, the longitudinal motion [the base of the LV moving towards the (normally) fixed apex] can be assessed while from using a parasternal (short or long-axis) view, the inward radial motion can be measured.

Either by calculating the spatial gradients of the obtained myocardial velocities[1] or by using a grayscale imaging approach (speckle tracking),[23] local myocardial deformation can be quantified. In reality, the deformation of a myocardial segment during the cardiac cycle is very complex[24] (*Figure 2B*) and contains both normal deformation (longitudinal shortening/lengthening, radial thickening/thinning, and circumferential shortening/lengthening) and shear (base–apex twisting, epi–endo circumferential shear, and epi–endo longitudinal shear).[1,25,26]

Figure 2C shows a typical longitudinal velocity and displacement (the temporal integral of the velocity) from a normal individual (using high frame-rate DMI). *Figure 2D* represents the corresponding deformation (strain) and speed of deformation (strain-rate). Note that there is a clear gradient from base to apex in both velocity and displacement, which corresponds to the stationarity of the apex within the thorax while the base moves towards it. In contrast, deformation is more or less homogenous throughout the (normal) myocardial wall. These patterns will be altered in cardiac pathologies (see further). Using Doppler-based approaches, mainly longitudinal and radial motion/

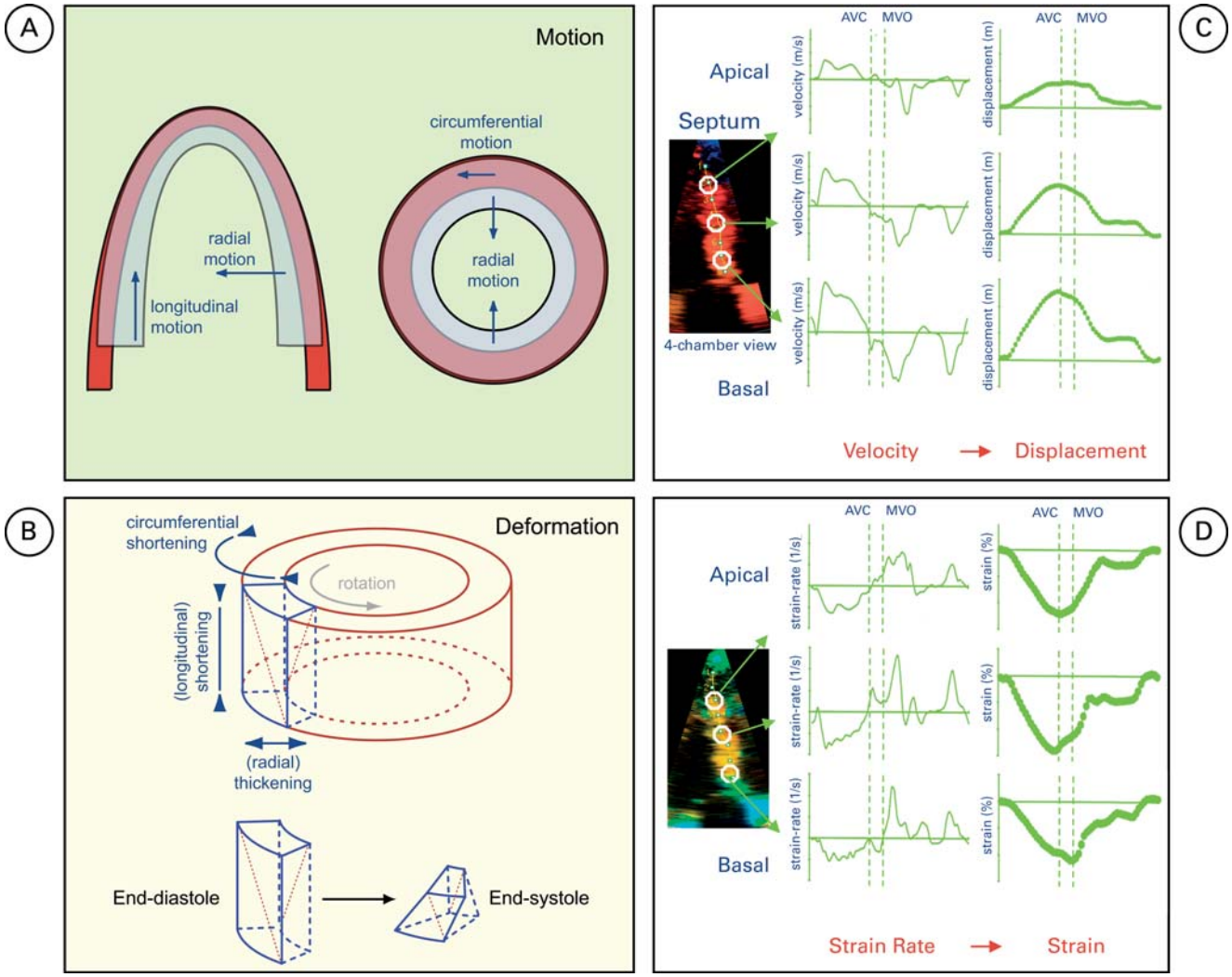

Figure 2 Myocardial motion and deformation consists of three major components: longitudinal, radial, and circumferential (*A* and *B*). The total deformation, from end-diastole to end-systole, of a myocardial segment is very complex and includes shortening, thickening, and shearing (*B*). Typical profiles for the velocity, displacement (*C*), and strain-rate, strain (*D*) traces during one cardiac cycle in normal myocardium. AVC, aortic valve closure; MVO, mitral valve opening.

deformation is studied, since it is difficult to align the circumferential motion with the ultrasound beam, as is required with this technique. With speckle tracking, longitudinal and circumferential motion/deformation is most commonly analysed, since the intrinsic spatial resolution of the images is limited, making it difficult to track the tissue within the (thin) wall. Moreover, the lateral resolution of ultrasound images is intrinsically less than in the axial direction, making it more difficult to assess radial deformation from an apical view.[27,28] Additionally, speckle tracking allows the assessment of cardiac rotation and torsion (if measured at different levels).[29] When using either of the approaches, it is important to note the inherent differences in the results. DMI works at higher temporal resolution ($>$ 150 Hz), making it more suited to assess that fast events, as are observed in velocities and strain-rates (especially in the iso-volumic periods), while for the quantification of displacements and strain, the inherent lower frame-rate used for speckle tracking ($<$ 90 Hz) would be sufficient. Speckle tracking has shown to be more reproducible and requires less user expertise, but inherently uses more spatial and temporal averaging of the obtained profiles, resulting in significantly lower values when compared with DMI and a decreased ability in detecting smaller abnormal regions.[27,28,30,31]

The relation between myocardial function (contractility) and regional deformation

When using myocardial motion or deformation to assess (dys-) function, it is important to understand the relation between intrinsic function (contractility) and the resulting motion/deformation.

In general, the relation between the forces acting up on an object and the resulting deformation of that object is described by Hooke's law. This law states that forces [mostly expressed as stress and with units pascal (Pa)] and deformation [mostly Lagrangian (relative) deformation and expressed as a percentage] are linked by the elasticity (with units Pa) of the object. The more elastic an object, the more it will be deformed by a certain force. This relation (which is also time-variant), when applied to myocardium, is illustrated in *Figure 3*.

In a myocardial segment, both the force developed 'by' the segment, as well as all forces developed 'on' the segment have to be taken into account. Obviously, the 'internal' contractile force (the intrinsic 'contractility' of the myocardium, a force trying to shorten the myocytes, thus resulting in negative deformation) is the most important. However, it has to be kept in mind that any piece of myocardium is always imbedded in a ventricle, resulting in external forces acting up on it (and mostly working in the opposite direction of the contractile force). These forces are described as the 'loading' of the tissue and consist of the local wall stress, caused by the intracavity pressure (whose influence is related to local geometry of the ventricle), and the interaction with neighbouring, contracting, segments (each contracting neighbouring segment will 'pull' the segment under investigation).

As for any object, the relation between all acting forces and the resultant deformation is ruled by the regional elasticity, which, for myocardium, translates in the fibre/matrix structure and the presence or absence of fibrosis and depositions. Also, it must be kept in mind that elasticity is not a constant, since, due to the matrix structure of the tissue, the more myocardium is stretched, the more difficult it becomes to stretch it even further.

In summary, the main factors influencing regional myocardial deformation are (*Figure 4*):

- Intrinsic contractility, i.e. the contractile force developed by the myocardium (influenced by tissue perfusion and electrical activation and being developed in the early part of the ejection phase, peaking around one-third of it).[32]
- Cavity pressure (often referred to as afterload and influenced by preload), whose influence is related to the local ventricular geometry.[33]
- Segment interaction (the influence of the contracting neighboring segment).[20]
- Tissue elasticity (which is dependent on the local histology (fibrosis) and on the amount that the myocardium is already stretched).[34]

Thus, these influencing factors consist of one active force (contractility), two passive forces (pressure and segment interaction), and the tissue properties. This is graphically presented in *Figure 4*, which shows a schematic short-axis cross-section of the left ventricle.

Clinical application

Coronary artery disease

Coronary artery disease and the underlying ischaemic substrates have been studied extensively using velocities and deformation [both based on invasive ultrasound crystal measurement and non-invasive imaging (echocardiography and magnetic resonance imaging)].[21,35–37] It was shown

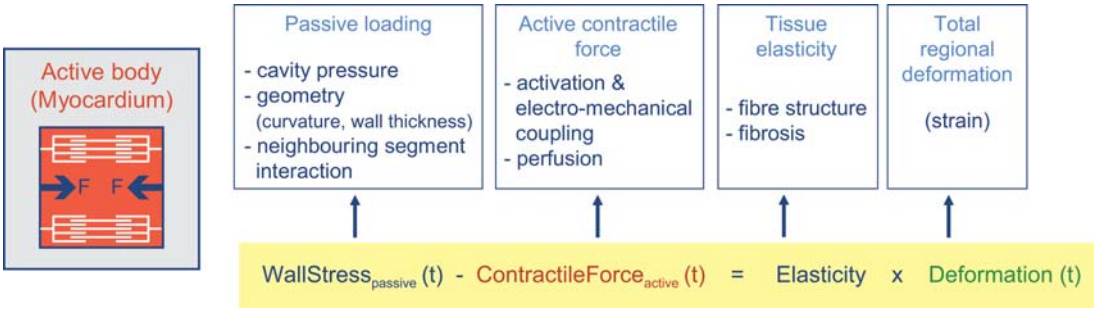

Figure 3 The relationship between local forces and deformation.

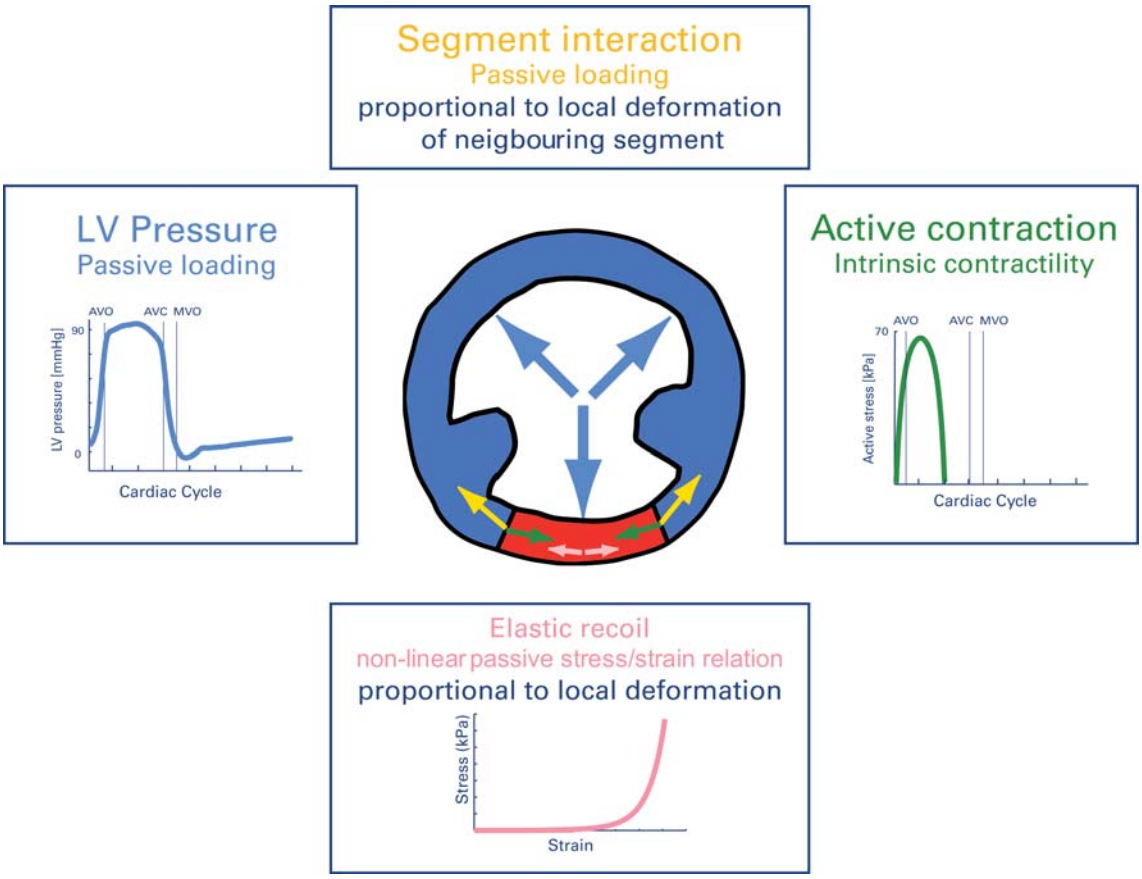

Figure 4 The local forces acting upon a myocardial segment.

that myocardial motion and deformation react very predictably on changes in regional perfusion of the presence of infarction.[17]

In summary, regional velocities as well as peak systolic strain-rate and end-systolic strain reduce linearly with a reduction in regional perfusion or the presence of sub-endocardial fibrosis. Simultaneously, post-systolic motion/deformation is developing. When challenged with dobutamine, acutely ischaemic tissue will show even less deformation, while post-systolic deformation is increased, whereas normal tissue shows increased deformation (continuously increasing strain-rate and increasing strain as long as filling is not reduced by increased heart-rate). In contrast, partial thickness chronic infarction will show a very moderate deformation increase (depending on the transmurality) when stimulated with dobutamine. Interestingly, while stunned myocardium shows decreased deformation at rest, associated with post-systolic deformation, when stimulated with dobutamine, systolic deformation almost restores to normal and post-systolic deformation almost completely disappears.[17] This behaviour of stunned myocardium can be attributed to myofibrillar oedema, increasing the spacing within the contractile elements of the myocardium and thus reducing the effective force it can develop.[38]

Additionally, it was shown that full pressure reperfusion of an acute infarct influences deformation. If reperfusion is within a short period of time after the onset of symptoms, the myocardial deformation will normalize quickly (potentially after some period of stunning). However, when reperfusion is within a time-span of ~1.5–6 h, interstitial myocardial oedema will develop, resulting in a sudden increase in end-diastolic wall thickness of the infarcted segment at the moment of reperfusion. This is associated with the total absence of regional deformation.[39,40] With reperfusion later than ~6 h after onset of symptoms, the myocardial wall has thinned and does not deform and reperfusion does not alter this significantly.

Thus, deformation analysis at baseline and its response to a dobutamine challenge enables to uniquely distinguish the different ischaemic substrates (*Figure 5*).

This makes the combination of the measurement of baseline deformation (in a lesser extent: motion), combined with the response to a dobutamine stress echo, a potent clinical tool for the assessment of the ischaemic substrate in a clinical patient.

Volume overload

As discussed earlier, deformation is also related to ventricular geometry. Dilatation is an adaptive mechanism used by the ventricle to cope with the problem of generating sufficient cardiac output to fulfil the needs of the body. There is a clear relationship between ventricular size and the generated stroke volume for a certain available contractile force. An enlarged ventricle can more easily generate a larger stroke volume than a smaller one. This can be easily understood since in a spherical or ellipsoid object, the volume of the outermost part is always larger than the volume of the innermost part, which means that similar deformation

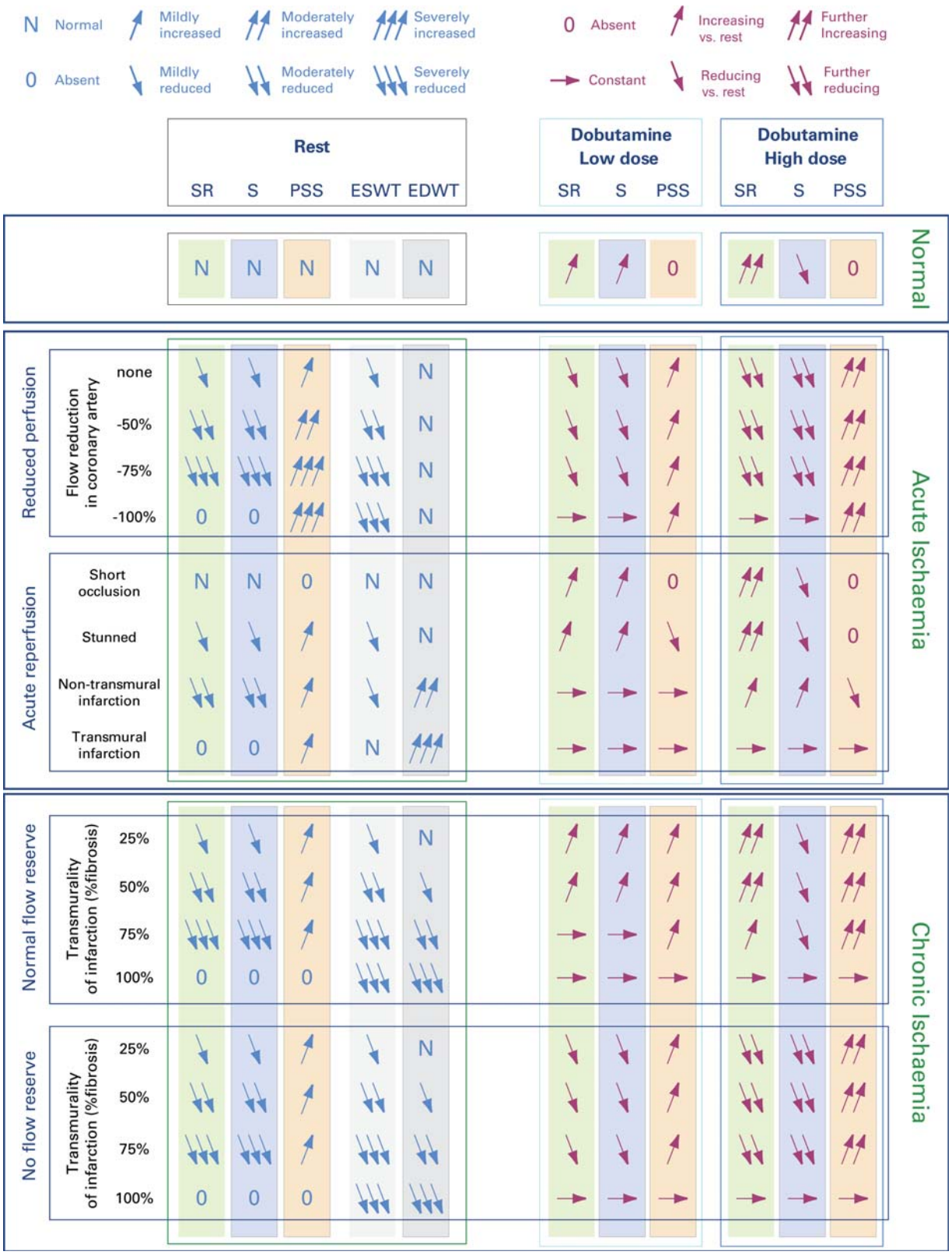

Figure 5 An overview of the regional deformation and wall thickness of the different ischaemic substrates at rest and how they respond to dobutamine. SR, peak systolic strain-rate; S, end-systolic strain; PSS, post-systolic strain; ESWT, end-systolic wall thickness; EDWT, end-diastolic wall thickness. From Sutherland *et al.*[1] with permission.

(determined by the contractile force) can generate a larger stroke volume in a dilated heart. Similarly, the same amount of stroke volume can be generated with less contractility in a dilated heart. Thus, as the ventricle dilates, with a preservation of stroke volume, regional deformation reduces without any change in contractility. However, when stroke

volume increases (as in valve regurgitation), myocardial deformation can increase. In these cases, only when contractility additionally reduces, there is a marked decrease in deformation.[7] Normalizing deformation with ventricular volume might be a useful approach to isolate the effect of geometry and changing contractility in volume overloaded ventricle.[7]

Pressure overload

Several cardiac conditions are associated with progressive remodelling of the ventricle. Examples of this include pressure or volume overload due to valvular stenosis or regurgitation, coronary artery disease with associated decreased contractility and fibrosis leading to ventricular dilatation, genetic abnormalities resulting in hypertrophy, and progressive development of local fibrosis, severe hypertension, conduction abnormalities, etc.

Remodelling is in the first instance a response to a problem with either the muscle itself or the environment in which it has to work and is an attempt to keep on fulfilling the heart's task—circulating the blood. However, since this is an abnormal situation with inherent mechanical disadvantages, in the long term, this will lead to irreversible damage to the muscle which evolves into ventricular dysfunction and heart failure. The early detection and follow-up of changes in cardiac function and myocardial properties is thus of major importance.

Myocardial velocities and deformation have proved useful in several conditions with altered myocardial properties or geometry.

With pressure overload pathology, the basal septal segment is the first to show changes (*Figure 6*). Both a decrease in strain (-rate) and the development of post-systolic motion/deformation is observed, as well as the development of localized hypertrophy.[9] With increasing overload the whole ventricle becomes hypertrophic and deforms less. The development of regional fibrosis further diminishes deformation. Thus, basal septal deformation is the most sensitive to changes in pressure overload pathology.

Genetic cardiomyopathies

Hypertrophic cardiomyopathy is associated with the presence of regional abnormalities in myocardial fibre arrangement, resulting in local dysfunctional myocardium. Using regional deformation analysis, these areas of histological abnormalities can be easily localized since they do not show any systolic deformation, while the rest of the (hypertrophic) segments still deform (although mostly much reduced compared with normal).

In genetic diseases such as Friedreich's Ataxia, Fabry Disease, or Duchenne Cardiomyopathy, regional deformation is first changing in the infero-lateral segment. As fibrosis develops first in this area, local strain-rates reduce and post-systolic deformation becomes apparent. This knowledge can be used to assess the efficacy of novel (very expensive) medical therapies.[15]

Left bundle branch block and cardiac resynchronization therapy

The availability of CRT has drastically changed the management of heart failure patients with dilated cardiomyopathies and left bundle branch block. In these patients, it is assumed that the abnormal conduction leads to a late activation of the lateral wall, resulting in an important reduction in cardiac function. Although ~70% of these patients clearly benefit from biventricular pacing, there is still a lot of debate about the best method to assess those patients that will most benefit from the treatment.[41,42]

The current approach to select potential responders is to get a more direct evaluation of late contractility by (echocardiographically) searching for the presence of mechanical dyssynchrony and trying to identify a severely delayed wall with potentially recruitable function, rather than looking only for ECG manifestations of ventricular conduction delay which poorly correlate with the actual ventricular mechanical events. Many methods have been proposed to quantify dyssynchrony. These can be classified as evaluating either the inter-ventricular delay (assessing the time difference between right and left ventricular contraction) or the

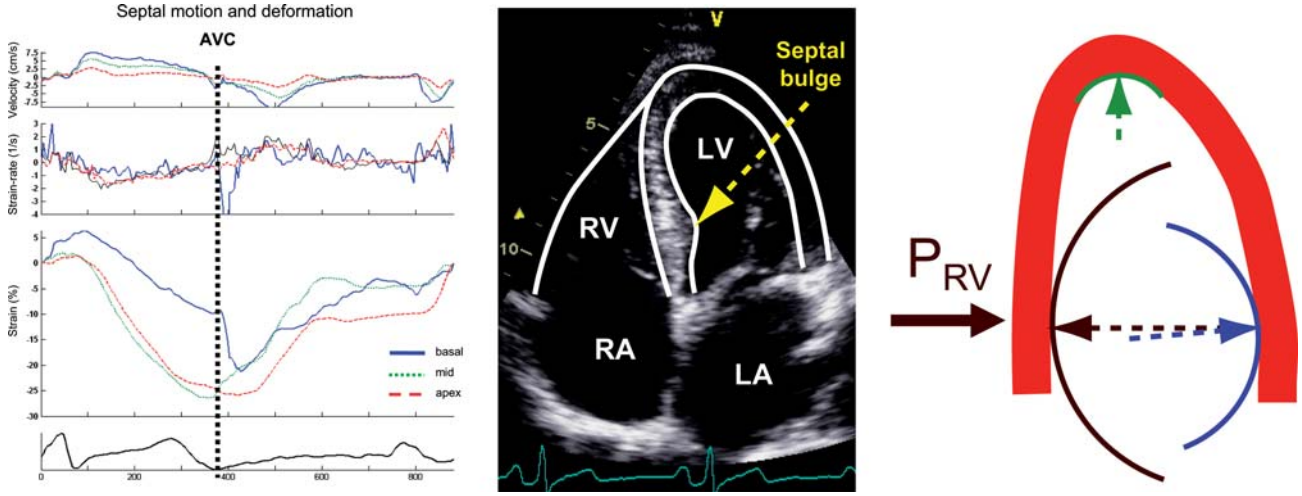

Figure 6 Hypertension results in ventricular remodelling, with the initial development of basal septal hypertrophy (septal bulge) due to increased wall stress associated with the bigger local radius of curvature. This is associated with reduced systolic deformation and the development of post-systolic deformation.

intra-ventricular delay (looking at timing of the motion/deformation of opposite ventricular walls).

To assess intra-ventricular delays, both M-mode (measuring the time difference between maximal septal and posterior excursion) and velocity/deformation based methods have been proposed.

Velocity and deformation-based methods mostly assess the time differences between maximal values from different myocardial segments. However, most methods are based on longitudinal motion. Patients eligible for CRT mostly have dilated ventricles with complex motion (including 'rocking') and low velocities. Especially the additional presence of infarcted areas makes the interpretation of the (longitudinal) velocity traces very challenging. Because local myocardial motion reflects both contractile function and the influence of other myocardial segments (tethering), using local velocities to extract information on timing of contraction is almost impossible. Especially in dilated hearts, with poor LV function, local motion can be importantly influenced, even by right ventricular motion.[43] This makes that most imaging parameters have proved to be not ideal to assess potential response to CRT.[44]

A more appropriate approach to assess these patients is searching for the underlying pathophysiological aetiology of their heart failure.[1] Besides problems with diastolic filling resulting from inappropriate atrio-ventricular delays, in a subgroup of patients there are typical and specific signs of LBBB and associated changes in cardiac mechanics.

'True' mechanical dyssynchrony originates from a delayed electrical activation of one of the myocardial walls. In a normal left ventricle, all segments are activated almost simultaneously and are thus deforming (longitudinal shortening and radial thickening) at the same time (*Figure 7A*). While the septum starts contracting, it contributes to pressure build up and ejection, but at the same time, it also pulls the lateral wall towards it. Similarly, the lateral wall will contribute to the pressure build up and ejection and will pull the septum towards it with an equal strength. The result is that both the septal and lateral annuli are dragged towards the apex, which remains stationary.

However, if there is a significant delay in the activation (and thus onset of contraction) of the lateral wall, the interaction between the walls changes significantly. When the septum is activated, there is a period where it is actively developing a contractile force and shortening while the contralateral wall is not. This means that it exerts a pulling effect on the latent opposite wall which is not counterbalanced by contraction of the latter. Because it now contracts against a reduced load, it will move/shorten faster than it would in a normal ventricle (*Figure 7B*). Additionally, this will result in an early stretching of the, still relaxed, lateral wall. As soon as the lateral wall is electrically activated, it starts to contract and thus will start in its turn to influence the septum. The pulling force from the (later activated) contracting lateral wall will stretch the septum.

This sequence of motion and deformation in septal and lateral wall can be easily appreciated from the regional motion and deformation traces. *Figure 7C* shows the (radial) velocities of the septal and infero-lateral wall of a normal individual and a patient with LBBB. While normally, the septal and infero-lateral wall show similar, but mirrored velocity (both moving inward, thus with opposite directions with regard to the transducer), in LBBB the septum shows a very large inward velocity as soon as it is activated, almost immediately followed by a fast outward motion when the infero-lateral wall is starting to contract. This can also be appreciated from slowed-down grayscale images, where the septum rapidly moves in and outward, resulting in a 'septal flash' motion. This 'septal flash' is not only fast septal motion, but is a result of fast septal deformation (*Figure 7D–F*) where there is rapid thickening of the septum (while the lateral wall is stretched) followed by thinning when the lateral wall contracts and thickens.

The combination of the unloaded contraction of the septum stretching the lateral wall followed by the late lateral wall contraction stretching the septum will result in very inefficient global contraction, in which a lot of energy and force is wasted in deforming opposing myocardium without contributing to ejection. This will ultimately lead to symptomatic heart failure. Correcting the difference in local activation and deformation using CRT will result in a marked improvement in cardiac function and reverse geometrical remodelling in patients showing these specific mechanical signs of LBBB.[45]

Diastolic function

Myocardial velocities have been suggested to be useful to assess diastolic function. Especially the ratio of early mitral flow velocities (E) and early basal myocardial velocities (E') was shown to correlate with relaxation abnormalities[46] and filling pressures.[47]

However, in order to understand its use and recognize the pitfalls of this approach, it is important to keep in mind what these velocities represent. When assessing diastolic function, one wants to get an idea on how much (volume) filling is happening in the early relaxation phase (related to ventricular compliance and intrinsic myocyte relaxation) and at which pressures (elevated end-diastolic and atrial pressure) this is taking place. When quantifying mitral blood flow velocities, one assesses the pressure gradient, between the atrium and the ventricle, driving the flow (*Figure 8*, left). This means that a high E can reflect as well (normal) low LV pressure with normal LA pressure, as well as elevated LA pressures (pseudo-normalization). When measuring basal myocardial velocities or ring motion, one assesses the dynamics of the basal LV displacement, which can be seen as a surrogate of global LV volume change (global LV deformation) (*Figure 8*, right). Thus, E' provides information on how much volume is entering the LV in the early filling period. This makes that the ratio E/E' provides information on how much volume enters the ventricle for a given LA–LV pressure gradient. This means that in all situations where E' does not properly reflect global LV volume changes (large infarctions, LV dilatation, LBBB, primary mitral regurgitation, hypertrophy, etc.), the ratio E/E' is not reflecting diastolic function and should be used with caution.[48,49]

Conclusion

Regional myocardial velocities and deformation prove to be a powerful tool to understand and quantify myocardial (dys-) function. Several cardiac conditions are associated with very specific changes in motion and deformation, which can be quantified using echocardiographic

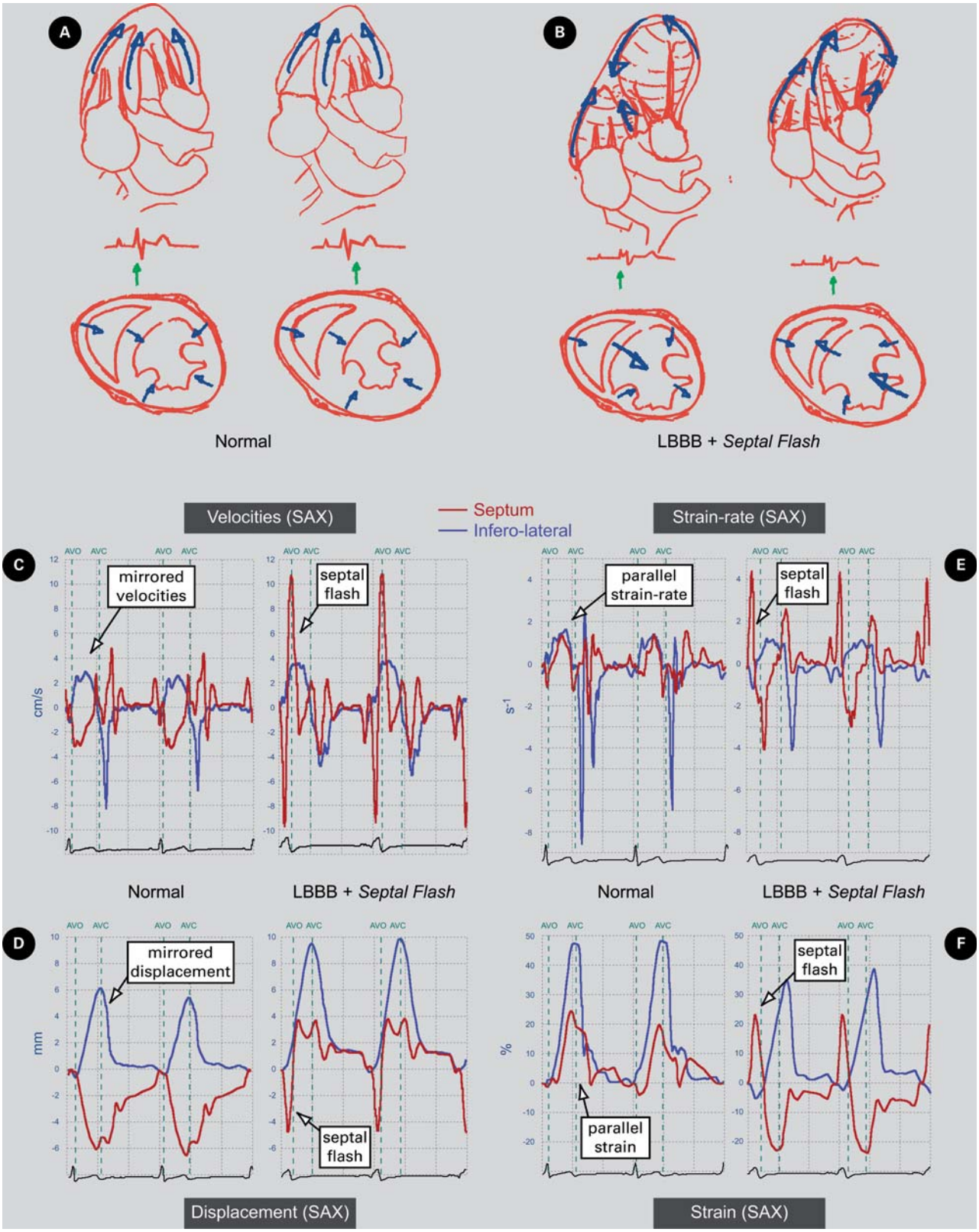

Figure 7 Myocardial velocities and deformation in patients with LBBB, compared with normal individuals.

techniques. Analysing myocardial deformation has provided important insights in cardiac mechanics and in the understanding of changes induced by a range of cardiac pathologies. Although none of the current techniques for ultrasound deformation assessment is perfect (DMI-strain has a steep learning curve and is very sensitive to the acquisition while speckle tracking strain works with low temporal resolution and important spatial and temporal smoothing),

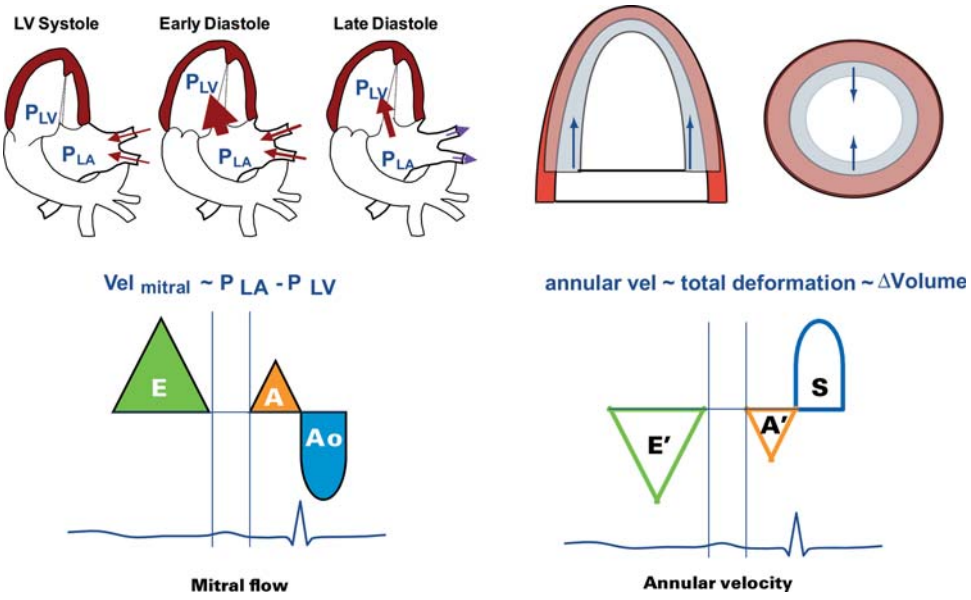

Figure 8 Mitral blood flow profiles and E wave velocity (left) are related to the pressure gradient between the left atrium and left ventricle, while the basal myocardial or mitral ring velocities and E' wave (right) are related to the overall deformation of the ventricle, thus indicating the global volume change during a certain period.

they still provide insight for the assessment of cardiac function in individual patients. Although the relation between local myocardial contractility and regional deformation is complex and dependent on loading and geometry, it was shown that the deformation assessment (potentially combined with dobutamine stimulation) provides useful additional information, especially for the clinical assessment of coronary artery disease and hypertrophic hearts.

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References

1. Sutherland GR, Hatle L, Claus P, D'hooge J, Bijnens BH. *Doppler Myocardial Imaging- A Textbook*. Hasselt, Belgium: BSWK; 2006.
2. Perk G, Tunick PA, Kronzon I. Non-Doppler two-dimensional strain imaging by echocardiography–from technical considerations to clinical applications. *J Am Soc Echocardiogr* 2007;**20**:234–43.
3. Jamal F, Strotmann J, Weidemann F, Kukulski T, D'hooge J, Bijnens B *et al*. Noninvasive quantification of the contractile reserve of stunned myocardium by ultrasonic strain rate and strain. *Circulation* 2001;**104**:1059–65.
4. Weidemann F, Jamal F, Sutherland GR, Claus P, Kowalski M, Hatle L *et al*. Myocardial function defined by strain rate and strain during alterations in inotropic states and heart rate. *Am J Physiol Heart Circ Physiol* 2002;**283**:H792–H799.
5. Thibault H, Derumeaux G. Assessment of myocardial ischemia and viability using tissue Doppler and deformation imaging: the lessons from the experimental studies. *Arch Cardiovasc Dis* 2008;**101**:61–8.
6. Voigt JU, Nixdorff U, Bogdan R, Exner B, Schmiedehausen K, Platsch G *et al*. Comparison of deformation imaging and velocity imaging for detecting regional inducible ischaemia during dobutamine stress echocardiography. *Eur Heart J* 2004;**25**:1517–25.
7. Marciniak A, Claus P, Sutherland GR, Marciniak M, Karu T, Baltabaeva A *et al*. Changes in systolic left ventricular function in isolated mitral regurgitation. A strain rate imaging study. *Eur Heart J* 2007;**28**:2627–36.
8. Marciniak A, Sutherland GR, Marciniak M, Claus P, Bijnens B, Jahangiri M. Myocardial deformation abnormalities in patients with aortic regurgitation: a strain rate imaging study. *Eur J Echocardiogr* 2008, Advance Access published on 25 June 2008; doi:10.1093/ejechocard/jen185.
9. Baltabaeva A, Marciniak M, Bijnens B, Moggridge J, He FJ, Antonios TF *et al*. Regional left ventricular deformation and geometry analysis provides insights in myocardial remodelling in mild to moderate hypertension. *Eur J Echocardiogr* 2008;**9**:501–8.
10. Vinereanu D, Florescu N, Sculthorpe N, Tweddel AC, Stephens MR, Fraser AG. Differentiation between pathologic and physiologic left ventricular hypertrophy by tissue Doppler assessment of long-axis function in patients with hypertrophic cardiomyopathy or systemic hypertension and in athletes. *Am J Cardiol* 2001;**88**:53–8.
11. Kato TS, Noda A, Izawa H, Yamada A, Obata K, Nagata K *et al*. Discrimination of nonobstructive hypertrophic cardiomyopathy from hypertensive left ventricular hypertrophy on the basis of strain rate imaging by tissue Doppler ultrasonography. *Circulation* 2004;**110**:3808–14.
12. Breithardt OA, Stellbrink C, Herbots L, Claus P, Sinha AM, Bijnens B *et al*. Cardiac resynchronization therapy can reverse abnormal myocardial strain distribution in patients with heart failure and left bundle branch block. *J Am Coll Cardiol* 2003;**42**:486–94.
13. Bellavia D, Pellikka PA, Abraham TP, Al-Zahrani GB, Dispenzieri A, Oh JK *et al*. Evidence of impaired left ventricular systolic function by Doppler myocardial imaging in patients with systemic amyloidosis and no evidence of cardiac involvement by standard two-dimensional and Doppler echocardiography. *Am J Cardiol* 2008;**101**:1039–45.
14. Eroglu E, D'hooge J, Sutherland GR, Marciniak A, Thijs D, Droogne W *et al*. Quantitative dobutamine stress echocardiography for the early detection of cardiac allograft vasculopathy in heart transplant recipients. *Heart* 2008;**94**:e3.
15. Weidemann F, Breunig F, Beer M, Sandstede J, Störk S, Voelker W *et al*. The variation of morphological and functional cardiac manifestation in

Fabry disease: potential implications for the time course of the disease. *Eur Heart J* 2005;**26**:1221–7.
16. Mertens L, Ganame J, Claus P, Goemans N, Thijs D, Eyskens B *et al*. Early Regional Myocardial Dysfunction in Young Patients With Duchenne Muscular Dystrophy. *J Am Soc Echocardiogr* 2008;**21**:1049–54.
17. Bijnens B, Claus P, Weidemann F, Strotmann J, Sutherland GR. Investigating cardiac function using motion and deformation analysis in the setting of coronary artery disease. *Circulation* 2007;**116**:2453–64.
18. Lang RM, Bierig M, Devereux RB, Flachskampf FA, Foster E, Pellikka PA *et al*. American Society of Echocardiography's Nomenclature and Standards Committee; Task Force on Chamber Quantification; American College of Cardiology Echocardiography Committee; American Heart Association; European Association of Echocardiography, European Society of Cardiology. Recommendations for chamber quantification. *Eur J Echocardiogr* 2006;**7**:79–108.
19. Aurigemma GP, Silver KH, Priest MA, Gaasch WH. Geometric changes allow normal ejection fraction despite depressed myocardial shortening in hypertensive left ventricular hypertrophy. *J Am Coll Cardiol* 1995; **26**:195–202.
20. Claus P, Weidemann F, Dommke C, Bito V, Heinzel FR, D'hooge J *et al*. Mechanisms of postsystolic thickening in ischemic myocardium: mathematical modelling and comparison with experimental ischemic substrates. *Ultrasound Med Biol* 2007;**33**:1963–70.
21. Weidemann F, Dommke C, Bijnens B, Claus P, D'hooge J, Mertens P *et al*. Defining the transmurality of a chronic myocardial infarction by ultrasonic strain rate imaging. The implications for identifying intramural viability - an experimental study. *Circulation* 2003;**107**:883–8.
22. Kowalski M, Herbots L, Weidemann F, Breithardt O, Strotmann J, Davidavicius G *et al*. One-dimensional ultrasonic strain and strain rate imaging: a new approach to the quantitation of regional myocardial function in patients with aortic stenosis. *Ultrasound Med Biol* 2003;**29**: 1085–92.
23. Modesto KM, Cauduro S, Dispenzieri A, Khandheria B, Belohlavek M, Lysyansky P *et al*. Two-dimensional acoustic pattern derived strain parameters closely correlate with one-dimensional tissue Doppler derived strain measurements. *Eur J Echocardiogr* 2006;**7**:315–21.
24. Sengupta PP, Krishnamoorthy VK, Korinek J, Narula J, Vannan MA, Lester SJ *et al*. Left ventricular form and function revisited: applied translational science to cardiovascular ultrasound imaging. *J Am Soc Echocardiogr* 2007;**20**:539–51.
25. Dokos S, Smaill BH, Young AA, LeGrice IJ. Shear properties of passive ventricular myocardium. *Am J Physiol Heart Circ Physiol* 2002;**283**: H2650–H2659.
26. Garot J, Pascal O, Diebold B, Derumeaux G, Gerber BL, Dubois-Rande JL *et al*. Alterations in systolic left ventricular twist after acute myocardial infarction. *Am J Physiol Heart Circ Physiol* 2002;**281**:H357–H362.
27. Langeland S, Wouters PF, Claus P, Leather HA, Bijnens B, Sutherland GR *et al*. Experimental assessment of a new research tool for the estimation of two-dimensional myocardial strain. *Ultrasound Med Biol* 2006;**32**: 1509–13.
28. Korinek J, Wang J, Sengupta PP, Miyazaki C, Kjaergaard J, McMahon E *et al*. Two-dimensional strain–a Doppler-independent ultrasound method for quantitation of regional deformation: validation in vitro and in vivo. *J Am Soc Echocardiogr* 2005;**18**:1247–53.
29. Helle-Valle T, Crosby J, Edvardsen T, Lyseggen E, Amundsen BH, Smith HJ *et al*. New noninvasive method for assessment of left ventricular rotation: speckle tracking echocardiography. *Circulation* 2005;**112**: 3149–56.
30. Ng AC, Tran da T, Newman M, Allman C, Vidaic J, Kadappu KK *et al*. Comparison of myocardial tissue velocities measured by two-dimensional speckle tracking and tissue Doppler imaging. *Am J Cardiol* 2008;**102**: 784–9.
31. Chan J, Hanekom L, Wong C, Leano R, Cho GY, Marwick TH. Differentiation of subendocardial and transmural infarction using two-dimensional strain rate imaging to assess short-axis and long-axis myocardial function. *J Am Coll Cardiol* 2006;**48**:2026–33.
32. Guccione JM, Le Prell GS, de Tombe PP, Hunter WC. Measurements of active myocardial tension under a wide range of physiological loading conditions. *J Biomech* 1997;**30**:189–92.
33. Grossman W, Jones D, McLaurin LP. Wall stress and patterns of hypertrophy in the human left ventricle. *J Clin Invest* 1975;**56**:56–64.
34. Guccione JM, Waldman LK, McCulloch AD. Mechanics of active contraction in cardiac muscle: Part II–Cylindrical models of the systolic left ventricle. *J Biomech Eng* 1993;**115**:82–90.
35. Edvardsen T, Aakhus S, Endresen K, Bjomerheim R, Smiseth O, Ihlen H. Acute regional myocardial ischaemia identified by 2-dimensional multiregion tissue Doppler imaging technique. *J Am Soc of Echocardiogr* 2000; **13**:986–94.
36. Derumeaux G, Ovize M, Loufoua J, Andre-Fouet X, Minaire Y, Cribier A *et al*. Doppler tissue imaging quantitates regional wall motion during myocardial ischaemia and reperfusion. *Circulation* 1998;**97**:1970–7.
37. Kukulski T, Jamal F, D'hooge J, Bijnens B, De Scheerder I, Sutherland GR. Acute changes in systolic and diastolic events during clinical coronary angioplasty: A comparison of regional velocity, strain rate and strain measurement. *J Am Soc Echocardiogr* 2002;**15**:1–12.
38. Bragadeesh T, Jayaweera AR, Pascotto M, Micari A, Le DE, Kramer CM *et al*. Post-ischaemic myocardial dysfunction (stunning) results from myofibrillar oedema. *Heart* 2008;**94**:166–71.
39. Turschner O, D'hooge J, Dommke C, Claus P, Verbeken E, De Scheerder I *et al*. The sequential changes in myocardial thickness and thickening which occur during acute transmural infarction, infarct reperfusion and the resultant expression of reperfusion injury. *Eur Heart J* 2004;**25**: 794–803.
40. Merli E, Sutherland GR, Bijnens B, Fischer A, Chaparro M, Karu T *et al*. Usefulness of changes in left ventricular wall thickness to predict full or partial pressure reperfusion in ST-elevation acute myocardial infarction. *Am J Cardiol* 2008;**102**:249–56.
41. Hawkins NM, Petrie MC, MacDonald MR, Hogg KJ, McMurray JJ. Selecting patients for cardiac resynchronization therapy: electrical or mechanical dyssynchrony? *Eur Heart J* 2006;**27**:1270–81.
42. Hayes D, Wang P, Sackner-Bernstein J, Asirvatham S. *Resynchronization and Defibrillation for Heart Failure: A Practical Approach*. Oxford, UK: Futura (Blackwell); 2004.
43. Marciniak M, Bijnens B, Baltabaeva A, Marciniak A, Parsai C, Claus P *et al*. Interventricular interaction as a possible mechanism for the presence of a biphasic systolic velocity profile in normal left ventricular free walls. *Heart* 2008;**94**:1058–64.
44. Chung ES, Leon AR, Tavazzi L, Sun JP, Nihoyannopoulos P, Merlino J *et al*. Results of the predictors of response to CRT (PROSPECT) trial. *Circulation* 2008;**117**:2608–16.
45. Parsai C, Bijnens B, Sutherland GR, Baltabaeva A, Claus P, Marciniak M *et al*. Toward understanding response to cardiac resynchronization therapy: left ventricular dyssynchrony is only one of multiple mechanisms. *Eur Heart J*, Advance Access published on 11 November 2008; doi:10.1093/eurheartj/ehn481.
46. Nagueh SF, Middleton KJ, Kopelen HA, Zoghbi WA, Quiñones MA. Doppler tissue imaging: a noninvasive technique for evaluation of left ventricular relaxation and estimation of filling pressures. *J Am Coll Cardiol* 1997;**30**: 1527–33.
47. Ommen SR, Nishimura RA, Appleton CP, Miller FA, Oh JK, Redfield MM *et al*. Clinical utility of Doppler echocardiography and tissue Doppler imaging in the estimation of left ventricular filling pressures: A comparative simultaneous Doppler-catheterization study. *Circulation* 2000;**102**: 1788–94.
48. D'souza KA, Mooney DJ, Russell AE, MacIsaac AI, Aylward PE, Prior DL. Abnormal septal motion affects early diastolic velocities at the septal and lateral mitral annulus, and impacts on estimation of the pulmonary capillary wedge pressure. *J Am Soc Echocardiogr* 2005;**18**:445–53.
49. Bruch C, Stypmann J, Gradaus R, Breithardt G, Wichter T. Usefulness of tissue Doppler imaging for estimation of filling pressures in patients with primary or secondary pure mitral regurgitation. *Am J Cardiol* 2004;**93**:324–8.