STRAIN AND STRAIN RATE ECHOCARDIOGRAPHY

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INTRODUCTION

Myocardial function is eventually determined by the shortening and lengthening of myocardium, i.e., myocardial deformation or strain. The exact and direct measure of myocardial deformation has been dependent on the in vitro analysis of myocardial length. This is not an ideal physiological approach due to the change of the surrounding environment, and the process is rather tedious. Thus, this in vitro approach is primarily a research tool.

Thanks to recently developed imaging techniques, regional myocardial deformation can now be measured. Using the myocardial tagging technique, one can measure myocardial strain with high accuracy. Currently, this is used as the clinical standard for the noninvasive evaluation of regional function.[1] However, due to cost and long time needed for off-line analysis, myocardial tagging by MRI is not routinely utilized for clinical purposes. In 1998 and then in 2000, Heidelm[2] and Urheim,[3] et al., reported that based on myocardial velocities by tissue Doppler imaging (TOI), the rate of myocardial deformation (strain rate or myocardial velocity gradient) can be calculated. In validation studies, Doppler-derived strain accurately reflected regional myocardial shortening and lengthening when compared to measurements by sonometric crystals. Since then, strain rate imaging (SRI) has been examined in animal and clinical studies for the assessment of cardiac function.

PRINCIPLES AND TECHNICAL ASPECTS

The term "strain" is used by material scientists to describe the deformation of different materials. One can determine natural strain (i.e., Eulerian strain) and Lagrangian strain. Natural strain refers to the spontaneous change in shape over time, and Lagrangian strain is the deformation of the material relative co its initial shape. Two different al$_{go}$ rithms have been used for che calculation of strain and strain rate using ultrasound.

The first algorithm is based on TOI.3 The principle for the calculation of longitudinal strain rate is explained in an apical four-chamber view image as follows (Figure 1): at time t_0, one end of che myocardium (1) was at the position of D1,$_0$ and another end (2) at the position of 02,$_0$; thus the length of chis part of myocardium at the time t_0 is (D2,$_0$-01,0) (say 1$_0$). If point 1 moves coward the apex at a velocit$_y$ of v_1 and point 2 at a velocity of v_2, then after a time period of dt, point 1 will be at the position given by: (Dl,$_0$+v$_i$" dt) and point 2 at the position of: (D2,$_0$+v/ dt). Then the length of myocardium (1$_f$) becomes [(D2t$_0$+v2* dt)-(Dlt$_0$+vl* dr)), i.e., 1$_0$ + (v_2-v$_1$)* t. Therefore, the accual length change during this time period is: (v_2-v_1)* c. The deformation of the myocardium (strain) from the starting length 1$_0$ is given by: ([(v_2-v_1)* t]/1 $_0$). The rate of deformation (strain rate or myocardial velocity gradient) is given by: (v_2-v_1)/1$_0$. Alternatively, strain is the integral of strain race during the above time period.

To calculate Lagrangian strain, 1$_0$ should be the initial length of the segment. In the beating heart, the end-diastolic length is substicuted. However, for natural strain, 10 is the actual myocardial length at the time point immediately before c. Since myocardial velocities can be easily measured by TOI, strain rate can be calculated.

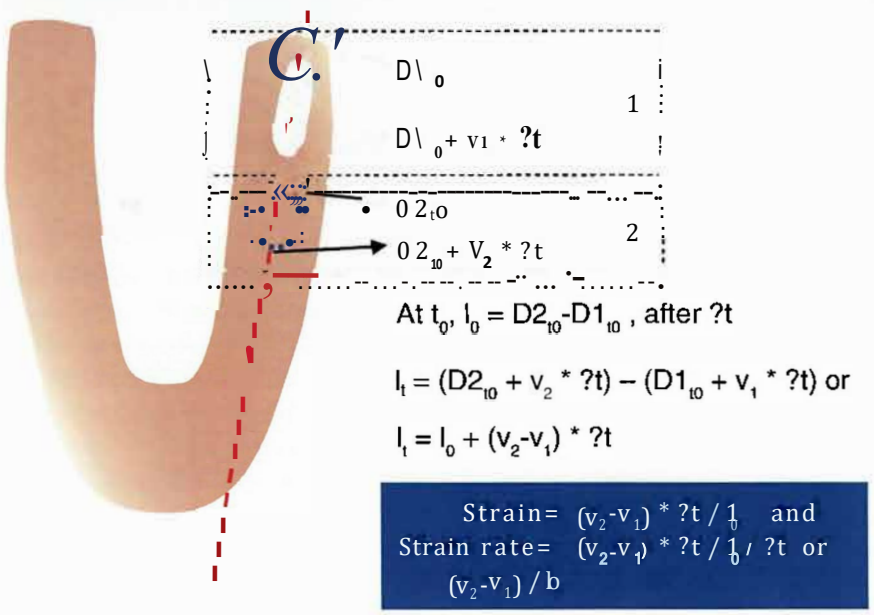

Figure 1. Cartoon illustrating the principle behind obtaining strain and strain rate using myocardial velocities by tissue Doppler. See text for details.

Figure 2 shows examples of strain race and strain signals acquired by che TD approach.

In a different algorithm, strain and strain rate are calculated using a technique that tracks the movemenc of speckles existing in myocardium in two-dimensional grayscale images.4•5 Thus, speckle tracking can follow the displacement of speckles in the myocardium and calculate the change in myocardial length between two spots of speckles, i.e., strain. Using this technique, it is possible to measure strain in che longitudinal, circumferencial and radial directions (Figures 3-5).

Using the strain and strain rare traces, we can measure amplitude parameters such as peak systolic strain, peak systolic strain race and diastolic strain rares and riming parameters such as time to the peak systolic strain and strain race, time co che onset of relaxation, ecc. In che 2-D speckle tracking package, we can measure che rotation and rate of rotation based on speckle displacement in addition co all of the above-mentioned parameters. Based on the difference of apical and basal twist, torsion can be calculated as well as the untwisting rate. These parameters provide new insights into cardiac function.

CLINICAL APPLICATION

Evaluation of regional function: The primary use of SRI is to evaluace regional function withom the influence of tethering. In a dog model, Urheim demonstrated chat Doppler-derived longitudinal myocardial strain was in good agreemenc with the peak strain calculated from sonomerric crys-

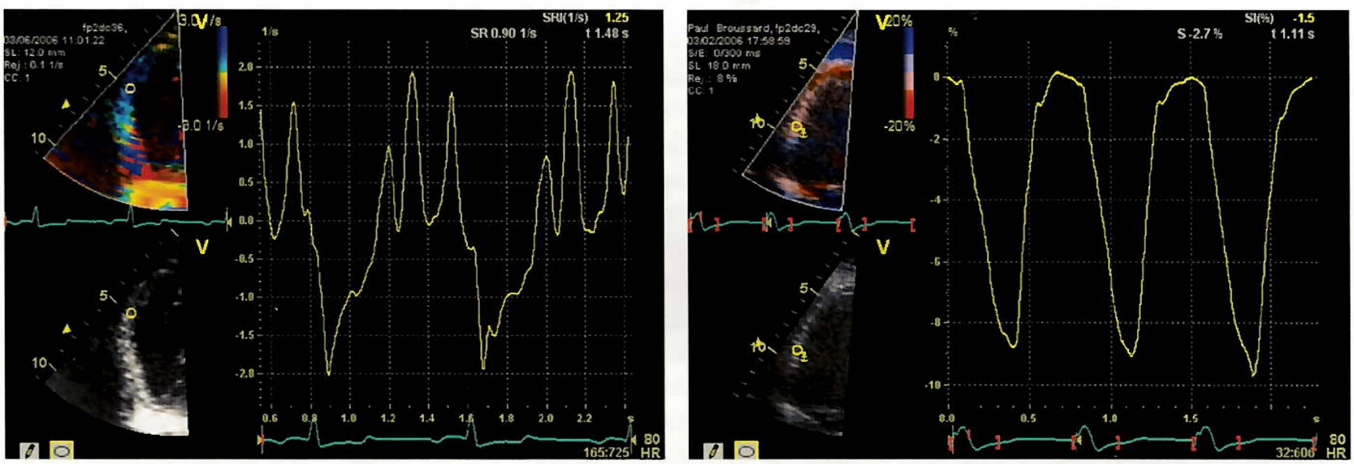

Figure 2. Example of SRI by Doppler. Left: Strain rate signal where S stands for systolic strain rate, MR for strain rate during isovolumic relaxation, E strain rate during early diastole and A: late diastolic strain rate. Right: Strain signal in the longitudinal plane which appears as a negative deflection in systole. Since the transducer is in an apiq;il position, systolic compression occurs in a direction away from the apex and hence the negative display in systole. In diastole, elongation occurs and results in positive signals.

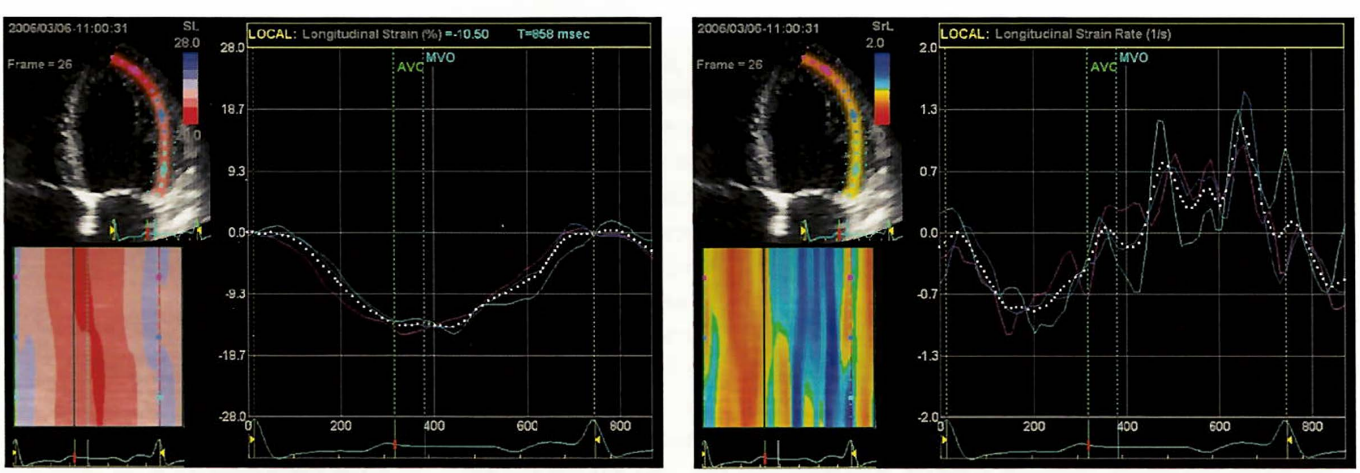

Figure 3. Strain (left) and strain rate (right) signals derived by speckle tracking in the longitudinal plane. The multiple curves display graphically the deformation indices at different points along the lateral wall. AVG and MVO are used for the timing of cardiac events, where AVG stands for aortic valve closure and MVO for mitral valve opening.

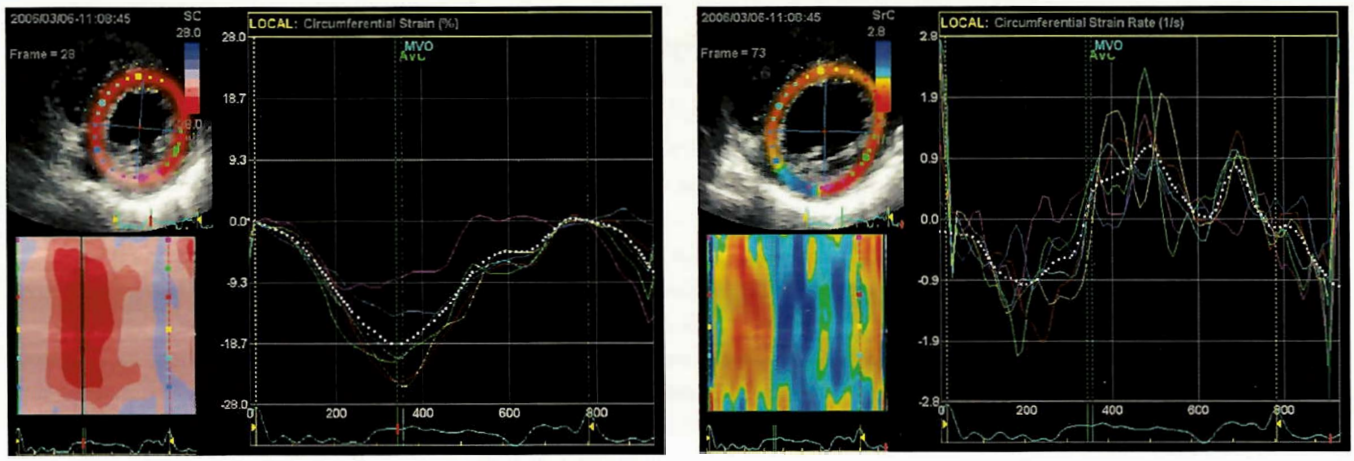

Figure 4. Circumferential strain (left) and strain rate (right) signals derived by speckle tracking in the short axis view at the mitral valve level. Abbreviations as in Figure 3.

tals.3 During LAD occlusion, strain calculated from both methods was reduced in the ischemic region but unaltered in non-ischemic sites. The assessment of regional myocardial function using velocity derived strain was further validated against tagged MRI in a clinical study with excellent correlacions.6 Abraham et al. used alcohol septal ablation in patients with hypertrophic cardiomyopathy as a clinical model to test whether SRI is superior to velocity measurements for the evaluacion of regional function. They found chat SRI can identify the depressed regional systolic function due to ablation-induced infarction. However, local velocities were unalcered.[7] Finally, SRI has also been shown to easily identify the presence of abnormal regional function in ischemic and infarct areas.8•9 In addition, SRI was able to differentiate transmural myocardial from non-transmural infarction.10 Timing parameters can detect abnormal mechanical events in the early stages of ischemia. Time to the onset of regional relaxation is one of these parameters. Delay of time to onset of diastolic thinning in subendocardial myocardial layer has been shown to identify the early stages of hypoperfusion during progressive coronary artery stenosis.11 In a parallel clinical application, time to onset of regional relaxation measured by SRI detected ischemia during dobutamine stress echocardiography with a reasonable sensitivicy.[12]

Evaluation of RV function: Evaluation of RV function can be challenging because of the complex RV geometry. In chat regard, TD has been applied to assess RV function.[13,14] However, chis application is limited in patients with patchy RV pathology such as arrhythmic right ventricle dysplasia. Recent reporcs indicate chat SRI may be able co accurately evaluate RV function.[15•18] Jamal et al. validated regional RV deformation parameters by SRI against measurements by sonometric crystals with good correlations.15 At the present time, the clinical application of chis method awaits additional scudies.

Assessmem of LV diastolic function: TD has been successfully applied co the evaluation of global LV diastolic function.[19] Specifically, the ratio of early mitral inflow velocity (E) to early diastolic velocity of mitral annulus (E/Ea) provides a reliable estimation of LV filling pressures in many clinical scenarios. However, regional myocardial dyssynchrony and dysfunccion may significantly influence the accuracy of Ea and E/Ea ratio for chat application. Whether SRI has an advantage over TOI in the estimation of LV filling pressures is of practical interest and yet co be investigated.

Due to the unique struccure and orientation of cardiac muscle fibers, the degree of LV twist and torsion are ocher aspects of LV mechanics chat can be examined.[20] LV torsion in combination with LV volume could present another method for the assessment of myocardial concraccilicy.[21] Furthermore, myocardial unrwiscing during early diastole provides the suction force for early diastolic filling.[22] Recent scudies have shown that apical rotation, LV torsion and untwisting could be assessed by using TD or speckle cracking cechniques.2325 However, there are limited data on che clinical application of LV torsion and untwisting and more importantly on their incremental value in the evaluation of LV mechanics.

Detection of myocardial viability: Noc only can myocardium at ischemic risk be depicted by strain rate echocardiography, but che viability of such myocardium with depressed function can be determined. Jamal er al. examined the contractile reserve of scunned myocardium using SRI in animal experimencs.[26] In patients with significant wall motion abnormality, the most frequent approach to evaluate myocardial viability is to evaluate the contractile reserve during the infusion of dobutamine. In chat regard, the feasibility of SRI for evaluating regional function during dobutamine stress has been documented.[27] Hoffman et al. showed chat an increase of longitudinal strain race <-0.23 s-1 during low-dose dobucamine can identify nonviable

myocardium {PET being the gold standard) wich a sensitivity of 83% and a specificity of 84%. However, the increase of regional systolic velocity had much lower accuracy.[28] Funhermore, Hanekom ec al. showed the incremental value of SRI parameters over conventional wall motion assessment ac low-dose dobutamine in identifying viable myocardium using functional recovery after coronary revascularization as che gold scandard.29 There are ocher reports on che value of early diastolic strain race in discinguishing viable from non-viable myocardium.30•31 However, additional studies are needed.

Poscsyscolic shortening (or chickening) has been reported to be an indicacor of myocardial viabili$_{ry}$ and can predict recovery of regional function.32 SRI is an ideal imaging modali$_{cy}$ for the quantitative analyses of the magnirude and timing of postsystolic shortening. Different degrees of ischemia can result in different patterns of systolic and poscsyscolic contraccion.33 Whether poscsyscolic shortening and some additional parameters such as late systolic lengthening34 can be most indicative of myocardial viability in the clinical setting is yet ro be determined.

Assessment of hypercrophic cardiomyopachy (HCM): HCM is a genetic disorder and the hiscology is characerized by myocardial hypertrophy, myocardial disarray and interstitial fibrosis.[35] Therefore, it is reasonable co posculace chat regional myocardial function in patients with HCM might be impaired. Evidence has shown chat TOI can decect abnormal myocardial contraction and relaxation irrespective of LV hypertrophy in animals and patients with known gene mutations.36•38 Recently, Kaeo et al. reported that SRI could distinguish HCM from significant LV hypertrophy caused by systemic hypertension.[39] A cutoffvalue of average syscolic scrain at -10.6% discriminated well between HCM patients and those with hypercension-induced LV hypertrophy (sensitivity of 85.0%, specificity of 100.0%). Alchough chere are some case reports on SRI for che evaluation of regional function in HCM patiencs,[39,40] the incremental value of SRI in chis disease awaits additional studies.

Selection of patients for cardiac resynchronization therapy (CRT): Global LV function can be compromised by either an absolute decrease of myocardial function or a discoordinate comraccion of myocardial segments due co intravemricular contraction del$_{ay}$ or both. In patients with heart failure and discoordinare LV contraction, aerial synchronized bi-ventricular pacing is an important treatment modalicy.41 The target of this therapy is co resynchronize LV contraction by activating the delayed contracting myocardium. Numerous studies have shown chac CRT significantly improves the mortality and morbidity in patients with advanced heart failure and left bundle block.42•44 This is accompanied by reverse left and right ventricle remodeling.45•46 However, the beneficial effects of CRT are not universal since 30% of such patients do not respond.47 This may be related to the fact chat the width of the QRS complex reflects the electrical dispersion, but noc necessarily mechanical dyssynchrony, with the latter determining LV function.

A number of studies have confirmed the face chat the width of QRS complex does not predict the responsiveness of the heart co CRT.48·50 On the other hand, indices indicative of intraventricular mechanical dyssynchrony are becter predictors of responsiveness of CRT. In that regard, echocardiography readily provides information on mechanical timing events at multiple sites of both ventricles. Pitzalis et al. reported chat the time delay between maximal septa! and posterior wall motion in M-mode images can predict the responsiveness of CRT at a cutoff value of 130ms.51 Additional studies have focused on myocardial velocity parameters by TOI.

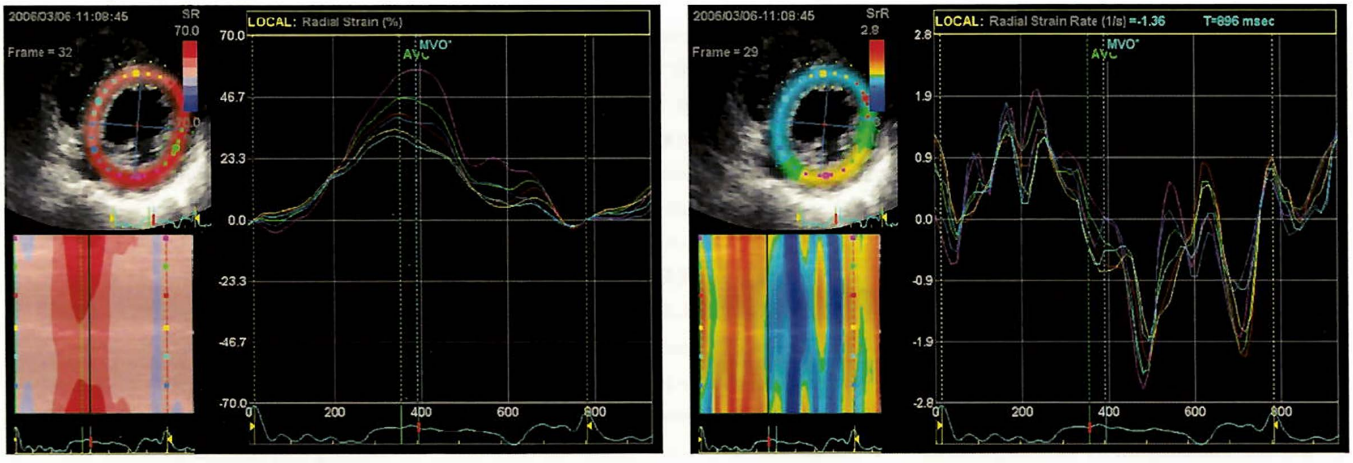

Figure 5. Radial strain (left) and strain rate (right) signals derived by speckle tracking in the short axis view at the mitral valve level. The direction of compression during systole is towards the transducer, whereas diastolic elongation is away from the transducer. Therefore, strain and strain rate graphic displays are in an opposite direction to that shown in the other figures. Abbreviations as in Figure 3.

These parameters included the difference between time to peak systolic velocity in basal inferior sepcum and anterior lateral wall, the maximal delay berween 4 or 6 basal LV segments, the standard deviation of time to peak systolic velocities in 12 basal and middle segmems[52] and the time to maximum displacement (time integral of myocardial velocity). Since strain and strain race can eliminate che tethering effect on tissue velocity, one might expect an incremental value of SRI in the evaluation of cardiac synchrony. However, the results with SRI have been controversial as Yu er al. noted that TD velocity is superior co SRI for predicting reverse remodeling.52 Notwithstanding the above study, the noisy SRI signals derived by TD may have precluded the acquisition of reliable results. The ultimate value of SRI in che evaluation of inter- and intra-ventricular mechanical synchrony and in selection of patients for CRT treatments deserves detailed analyses using high-resolution imaging systems. In particular, tissue speckle tracking techniques may be useful.

PERSPECTIVES

Alchough numerous studies have shown that SRI can provide important information in the diagnosis of various cardiac diseases, this imaging modality still has limitations for routine clinical application. This may be due co several reasons.

First, SRI derived from myocardial velocities by TOI has substantial variability.53 Such variability may originate from the noisy tissue Doppler signals, which is amplified when the myocardial velociry gradient or strain rate is derived. Tissue tracking algorithms appear promising and may overcome this limitation. Whether tissue speckle tracking can provide a higher reproducibility for measurement of strain and strain rate measurements is yec co be determined.

Second, SRI derived by TD is highly dependent on the angle berween Doppler beam and the plane of tissue motion. In clinical practice, ir can be challenging co optimize the alignment of rhe Doppler beam and a given myocardial segment, especially in patients with a dilated heart. Again, tissue tracking overcomes this angle dependency, but its superiority needs to be shown in head co head comparisons using sonometric crystals and cardiac magnetic resonance.

Limitations co the tissue speckle technique include irs dependency on optimal image quality co achieve an unambiguous appearance of speckles for subsequent tracking. In addition, the detection of cardiac events of very short durations may nor be possible using this technique.

Therefore, more information may be derived by using TD and/or tissue speckle tracking co obtain strain rate and strain in different situations based on technical and clinical factors.

CONCLUSIONS

Strain rate imaging for the evaluation of cardiac function has been validated in animal and clinical models. SRI can be used co detect ischemia and can also identify myocardial viability. The average of systolic strain from multiple LV segments can differentiate hypertrophic cardiomyopathy and LV hypertrophy caused by systemic hypertension. SRI can play a role in identifying the likely responders after CRT. Although there are many potential applications to SRI, technical improvements that increase the signal-co-noise ratio and additional studies showing its incremental value over conventional measurements are needed.

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