Radial Strain Delay Based on Segmental Timing and Strain Amplitude Predicts Left Ventricular Reverse Remodeling and Survival After Cardiac Resynchronization Therapy

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Background—Dyssynchrony assessment based on the timing of regional contraction is inherently independent of underlying myocardial contractility. We tested the hypothesis that patient selection for cardiac resynchronization therapy (CRT) would be enhanced using a parameter derived from the net radial strain delay (RSD) for the 12 basal and mid–left ventricular segments (calculated radial strain delay RSD [RSDc]), based on not only timing but also amplitude of segmental strain.

Methods and Results—Echocardiographic data were analyzed in 240 patients with symptomatic heart failure undergoing CRT (New York Heart Association class III/IV; QRS >120 milliseconds; ejection fraction, 23±7%). RSDc was calculated as the sum of difference between peak radial strain and radial strain at aortic valve closure before CRT implantation. CRT response was defined as >15% reduction in left ventricular end-systolic volume at 6 months. In a derivation group (n=102), RSDc was higher in responders compared with nonresponders (74±39% versus 29±15%; P<0.001) and related to the change in left ventricular end-systolic volume (r=−0.53; P<0.001). RSDc >40% predicted remodeling (sensitivity, 87%; specificity, 88%). In the validation group (n=108), RSDc similarly predicted response (sensitivity, 89%; specificity, 84%). Survival at long-term follow-up was greater in patients with RSDc >40% (P<0.0001).

Conclusions—RSDc, based on both the timing and the amplitude of segmental strain, has a strong predictive value for CRT remodeling response and long-term survival. (Circ Cardiovasc Imaging. 2013;6:177-184.)

Key Words: cardiac dysfunction ■ cardiac resynchronization therapy ■ speckle-tracking echocardiography

Echocardiographic parameters using dyssynchrony measurement by tissue Doppler and strain imaging have been disappointing for predicting cardiac resynchronization therapy (CRT) response.1,2 Although most major trials and current guidelines recommend CRT on the basis of QRS width (>120 milliseconds), several studies recognize that identification of mechanical dyssynchrony may enhance patient selection.3,4 However, the use of these techniques was not supported in 2 major multicenter trials. In the PROSPECT (Predictors of response to CRT) trial5 of nearly 500 patients, echocardiographic parameters of dyssynchrony offered limited sensitivity, specificity, and reproducibility for predicting CRT response. In the ReThinQ (Resynchronization Therapy In Normal QRS) trial6 of patients with a narrow QRS duration and severe left ventricular (LV) dysfunction, including evidence of mechanical dyssynchrony, CRT conferred no benefit. Extensive myocardial scar also limits CRT response, suggesting that characterization of the underlying myocardial substrate should be considered together with timing of segmental contraction to predict LV reverse remodeling.7,8 Speckle-tracking analysis has emerged as a technique with the potential to enhance patient selection for CRT with a >130-millisecond difference in the delay between the time to peak anteroseptal and posterior wall radial strain predicting response (sensitivity, 88%; specificity, 83%).9 We, therefore, tested the hypothesis that patient selection for CRT would be enhanced using a strain-based parameter incorporating both timing of myocardial segmental motion and amplitude of deformation, a potential measure of contractile reserve. We assessed a radial strain delay (RSD) parameter (based conceptually on the strain delay index reported by Lim et al10) and compared this with previously reported dyssynchrony measures to determine improvements in predefined end points of LV volume after CRT, as well as prognosis.
York Heart Association functional class III or IV heart failure, and impaired LV systolic function (LV ejection fraction ≤35%), despite optimal medical treatment. All patients underwent detailed clinical assessment, including a 6-minute walk test and Minnesota Living with Heart Failure Questionnaire, and baseline echocardiography before scheduled device therapy. Radial strain speckle-tracking analysis was performed on the parasternal 2-dimensional gray scale images of the 12 nonapical segments in each patient. After CRT, baseline clinical and echocardiographic assessments were repeated at 6 months, and response was defined as a ≥15% reduction in LV end-systolic volume (LVESV). Mortality data were collected with the longest follow-up of almost 4 years. The study was approved by the local ethics committee, and all participants gave fully informed written consent.

CRT Implantation
An 8F guiding catheter was used to position the LV lead. Final LV lead position was determined by biplane fluoroscopy and lateral and frontal chest radiographs. The right atrial lead was positioned in the right atrial appendage, and the right ventricular lead was placed according to operator preference in the midseptum or right ventricular apex. Atrioventricular and interventricular delays were optimized by echocardiography in all patients according to the highest velocity-time integrals from the pulsed wave Doppler of the transmitral inflow and LV outflow tract, respectively, as previously described. Devices were programmed in DDD mode (lower rate limit, 40) to achieve atrial synchronous biventricular pacing.

Echocardiography
Standard 2-dimensional and tissue Doppler imaging (TDI) was performed in all subjects using a 3.5-MHz phased array transducer (Vivid 7; General Electric Medical Systems, Horten, Norway). The gray scale, color Doppler, and tissue color Doppler data were acquired in a cine-loop format and digitally stored for postprocessing offline (version 7.0, GE EchoPAC, Horten, Norway). LV end-diastolic volume, LVESV, and LV ejection fraction were calculated using the Simpson biplane guidelines. Interventricular mechanical dyssynchrony (IVMD) was determined as the difference in time from QRS onset and the beginning of pulmonary and aortic ejection from pulsed wave Doppler measurements in the pulmonary and aortic outflow tracts, respectively. Intraventricular dyssynchrony was assessed in all patients by speckle-tracking echocardiography and tissue Doppler imaging.

Speckle-Tracking Echocardiography
Speckle-tracking analysis of the preimplantation gray scale basal and mid-LV short-axis images was performed using a standardized approach as previously described. All images were recorded with a frame rate of >40 Hz. The endocardial border was traced just within the endocardium using a point-and-click technique in end systole, and particular care was taken to adjust tracking of all segments. A second larger concentric circle was then automatically generated and manually adjusted near the epicardium such that the area of interest included the entire myocardial wall. The width of the epicardial circle was either increased or decreased where necessary to account for variation in wall thickness. The image was then played so that tracking in the region of interest could be fine-tuned by visual assessment to ensure that all wall segments tracked appropriately throughout the cardiac cycle and that the sectors defining each wall segment were adjusted appropriately.

Radial Strain Delay
The derived measure of RSD, is designed to incorporate both the amplitude and the timing of myocardial regional deformation. Areas of scar do not contribute effectively to myocardial ejection, and the extent of myocardial scar is inversely proportional to the extent of LV reverse remodeling after CRT. Myocardial deformation analysis has the inherent advantage of distinguishing active contraction from passive movement or tethering. Analysis of the amplitude of regional strain by speckle-tracking echocardiography has the potential to

![Figure 1. Concept of the radial strain delay using speckle-tracking analysis.](http://circ-imaging.ahajournals.org/)

Figure 1. Concept of the radial strain delay using speckle-tracking analysis. Schematic representation of wasted energy according to timing of myocardial deformation (dyssynchrony) and amplitude (contractility) by radial strain. A, In a normal segment (gray), peak deformation occurs close to aortic valve closure, contributing fully to end-systolic (ES) function. Peak ejection is assumed to occur at end systole, at the point of aortic valve closure (AVC) defined by pulsed wave Doppler. Early and late deformation in segments with preserved contractility will not fully contribute to end-systolic function. The wasted energy is represented by the difference in strain amplitude at peak and end systole for these segments (red). B, The degree of wasted energy increases as segments with preserved contractility become more delayed. C, In delayed segments with preserved amplitude (contractility), the degree of wasted energy is greater than in low-amplitude segments (minimal residual contractility or scar).
identify potentially recruitable myocardium (Figure 1). Areas of low amplitude probably represent scar, and LV lead placement over areas of low-amplitude radial strain is associated with a poor response to CRT. Intraventricular conduction delay induces both early and late segmental contraction either before peak ejection or after closure of the aortic valve, thereby reducing the efficiency of myocardial contraction, resulting in wasted energy. Because the amplitude of myocardial strain is not measured in standard dyssynchrony parameters, which are based on timing alone, the extent of wasted energy is not taken into account. This concept of wasted energy has been proposed and quantified previously using speckle-tracking longitudinal strain delay and has shown promise in identifying responders and nonresponders to CRT. Using a similar principle, we quantified the extent of wasted energy using RSD, calculated as peak radial strain minus radial strain at peak ejection (aortic valve closure) for the 12 nonapical segments, expressed as \( \sum_{n=1}^{12} (RS_{n, \text{peak}} - RS_{n, \text{AVC}}) \) (Figure 2). RSD(mid), for the 6 midmyocardial segments, expressed as \( \sum_{n=1}^{6} (RS_{n, \text{peak}} - RS_{n, \text{AVC}}) \) was also calculated.

**Timing-Based Dyssynchrony Parameters**

In addition to the RSD, dyssynchrony parameters based on the timing from onset of the QRS to peak strain were assessed. Anteroseptal to posterior (AS-P) wall delay using radial speckle tracking was calculated as the difference between time and peak radial strain from QRS onset of the anteroventral and posterior segments of the mid-LV. Rs-SD12, defined as the SD of the time to peak strain of the 12 nonapical segments using speckle-tracking radial strain, was also assessed. Dyssynchrony was additionally assessed by tissue Doppler imaging techniques in all patients. Dyssynchrony by TDI was determined as the maximal time difference in peak systolic velocities between the basal septum and the lateral segment (Ts-SL delay) and the SD of the time-to-peak systolic velocity of the 12 nonapical segments (Ts-SD12) as previously reported.

**Follow-up**

The primary end point of LV remodeling at 6 months was defined as a >15% reduction in LVESV. Secondary end points were clinical response of >1 class improvement in New York Heart Association functional status at 6 months of survival.

**Statistical Analysis**

Data are presented as mean±SD. For continuous data, Student t test was used to compare means between paired and unpaired groups. A value of \( P <0.05 \) was considered statistically significant. Receiver-operating characteristic curves were determined to evaluate the potential of each dyssynchrony parameter to predict CRT response. Optimal cutoff values for AS-P, Ts-SL, and Ts-SD12 were taken as 130, 65, and 33 milliseconds, respectively, as previously reported. For the remaining dyssynchrony parameters, optimal cutoff values were chosen to maximize the Youden index (sensitivity+specificity−1). Correlation was used to compare LVESV reduction and each of the dyssynchrony parameters. Kaplan–Meier curves were plotted for survival, and the log rank test was used to compare the groups. Reproducibility was assessed in 20 randomly selected data sets. Intraobserver and interobserver variability was expressed as the SD of the difference between 2 paired measurements and as a percentage of variability (SD divided by the average value of the variable). Intraobserver and interobserver variability for RSD by speckle-tracking strain was based on identical data sets.

**Results**

**Patient Baseline Characteristics**

In 240 consecutive patients assessed for CRT, a total of 18 subjects (8%; n=11 in the derivation group) had inadequate echocardiographic images for analysis. Implantation of a LV lead was not possible in 5 patients (2%; n=3 in the derivation group). Follow-up data were incomplete at 6 months in 7 patients because of failure to attend for echocardiography (n=4 in the derivation group), resulting in complete data in 102 patients in the derivation group and 108 patients in the validation group. The baseline characteristics of all patients are presented in Table 1.

**Feasibility and Reproducibility of Dyssynchrony Parameters and RSD**

Feasibility for dyssynchrony parameters were Ts-SL in 178 patients (85%) and Ts-SD12 in 170 patients (81%), AS-P delay in 181 patients (86%), Rs-SD12 in 177 patients (84%), RSD, in 178 patients (85%), and IVMD in 195 patients (93%). Intraobserver and interobserver reproducibilities were 5% (10%) and 7% (14%), respectively, for calculation of the RSD. For additional dyssynchrony parameters, intraobserver and interobserver reproducibilities were 20 milliseconds (10%) and 28 milliseconds (14%) for AS-P delay; 15 milliseconds (12%) and 21 milliseconds (16%) for Rs-SD12; 4 milliseconds (10%) and 5 milliseconds (12%) for IVMD; 8 milliseconds (11%) and 11
Table 1. Baseline Characteristics of All Patients

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>All Patients (n=210)</th>
<th>Derivation Group (n=102)</th>
<th>Validation Group (n=108)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>71±10</td>
<td>69±10</td>
<td>72±11</td>
</tr>
<tr>
<td>Male, n (%)</td>
<td>161 (76.7)</td>
<td>79 (77.5)</td>
<td>82 (75.9)</td>
</tr>
<tr>
<td>NYHA III/IV, n (%)</td>
<td>195/15</td>
<td>95/7</td>
<td>100/8</td>
</tr>
<tr>
<td>Ischemic cardiomyopathy, n (%)</td>
<td>115 (54.8)</td>
<td>55 (53.9)</td>
<td>60 (55.6)</td>
</tr>
<tr>
<td>Previous CABG, n (%)</td>
<td>61 (29.0)</td>
<td>28 (27.3)</td>
<td>33 (30.6)</td>
</tr>
<tr>
<td>Diabetes mellitus, n (%)</td>
<td>49 (35.0)</td>
<td>34 (33.3)</td>
<td>31 (28.7)</td>
</tr>
<tr>
<td>LVEF, %</td>
<td>23±7</td>
<td>23±7</td>
<td>23±7</td>
</tr>
<tr>
<td>Moderate/severe mitral regurgitation, n (%)</td>
<td>62 (29.5)</td>
<td>27 (26.5)</td>
<td>35 (32.4)</td>
</tr>
<tr>
<td>ACEi or ARB, n (%)</td>
<td>201 (95.7)</td>
<td>98 (96.1)</td>
<td>103 (95.4)</td>
</tr>
<tr>
<td>β-Blockers, n (%)</td>
<td>158 (75.2)</td>
<td>78 (76.5)</td>
<td>80 (74.1)</td>
</tr>
<tr>
<td>Spironolactone, n (%)</td>
<td>134 (63.8)</td>
<td>64 (62.7)</td>
<td>70 (68.4)</td>
</tr>
<tr>
<td>Loop diuretics, n (%)</td>
<td>210 (100)</td>
<td>102 (100)</td>
<td>108 (100)</td>
</tr>
<tr>
<td>Lateral LV lead, n (%)</td>
<td>96 (45.7)</td>
<td>48 (47.1)</td>
<td>48 (44.4)</td>
</tr>
<tr>
<td>Posterior LV lead, n (%)</td>
<td>87 (41.4)</td>
<td>42 (41.2)</td>
<td>45 (40.7)</td>
</tr>
<tr>
<td>Inferior LV lead, n (%)</td>
<td>16 (7.6)</td>
<td>7 (6.9)</td>
<td>9 (8.3)</td>
</tr>
<tr>
<td>Anterior LV lead, n (%)</td>
<td>11 (5.2)</td>
<td>5 (4.9)</td>
<td>6 (5.6)</td>
</tr>
<tr>
<td>RV septal lead, n (%)</td>
<td>91 (43.3)</td>
<td>43 (42.2)</td>
<td>48 (44.4)</td>
</tr>
<tr>
<td>RV apical lead, n (%)</td>
<td>119 (56.7)</td>
<td>59 (57.8)</td>
<td>60 (55.6)</td>
</tr>
<tr>
<td>CRT–defibrillator, n (%)</td>
<td>102 (48.6)</td>
<td>47 (46.1)</td>
<td>55 (50.9)</td>
</tr>
<tr>
<td>CRT–pacemaker, n (%)</td>
<td>108 (51.4)</td>
<td>55 (53.9)</td>
<td>53 (49.1)</td>
</tr>
</tbody>
</table>

Data are presented as mean±SD when appropriate. ACEi indicates angiotensin-converting enzyme inhibitors; ARB, angiotensin receptor blockers; AS-P, anteroseptal to posterior wall delay; CABG, coronary artery bypass grafting; CRT, cardiac resynchronization therapy; LV, left ventricular; LVEDV, left ventricular end-diastolic volume; LVEF, left ventricular ejection fraction; LVESV, left ventricular end-systolic volume; NYHA, New York Heart Association; and RV, right ventricular.

milliseconds (15%) for Ts-SL; and 4 milliseconds (10%) and 5 milliseconds (13%) for Ts-SD12, respectively.

Derivation Group

Response to CRT

After 6 months of CRT, New York Heart Association class improved in 71 patients (69.6%), was unchanged in 16 patients (15.7%), and worsened in 11 patients (10.8%). Four patients had died and were classified as nonresponders. Of the remaining patients in whom LV reverse remodeling data were available, LVESV reduced by >15% in 62 patients, reduced between 0% and 15% in 29 patients (28.4%), and increased in 9 patients (8.8%) giving a response rate of 60.8% for the total cohort. The changes in functional and echocardiographic variables before and after 6 months of treatment are reported in Table 2. Responders by volume reduction compared with nonresponders exhibited lower New York Heart Association class, greater 6-minute walk test distances, and improved quality of life scores.

Dyssynchrony Parameters Between Responders and Nonresponders

Dyssynchrony parameters that differed between volumetric responders and nonresponders were the RSDc (74±39% versus 29±15%; P<0.001), RSDc(mid) (45.8±29% versus 16.4±12.3%; P<0.001), AS-P delay (226±154 ms versus 122±93 ms; P<0.001), Rs-SD12 (144±100% versus 100±58%; P<0.001), and IVMD (42±22% versus 35±26%; P=0.02). Neither the Ts-SL nor the Ts-SD12 differed significantly between the 2 groups (Table 3).

Prediction of LV Reverse Remodeling After CRT

RSDc was related to the reduction in LVESV at 6 months (r=−0.53; P<0.001; Figure 3) and did not differ in patients with an ischemic and nonischemic basis for their heart failure (r=−0.51; P<0.001 versus r=0.54; P<0.001). RSDc(mid) was similarly related to the reduction in LVESV at 6 months (r=−0.53; P<0.001). Both the parameters displayed a stronger correlation LV reverse remodeling than the AS-P delay (r=−0.28; P=0.02), Rs-SD12 (r=−0.29; P=0.007), and IVMD (r=−0.29; P=0.008). However, there was no correlation with the change in LVESV at 6 months for either Ts-SL (r=−0.18; P=0.11) or Ts-SD12 (r=−0.19; P=0.12). Using receiver-operating characteristic curve analysis, a cutoff value of 40% for RSDc predicted a >15% reduction of LVESV with a sensitivity of 87% and specificity of 88% (Figure 4). A cutoff value of 23% for RSDc(mid) predicted >15% reduction of LVESV with a sensitivity of 81% and specificity of 83%. Receiver-operating characteristic curve analysis and the sensitivities and specificities of all dyssynchrony parameters assessed are presented in Table 3. RSDc had the highest sensitivity and specificity and was evaluated in a validation cohort.

Validation Group

RSD and Prediction of CRT Response

Seventy-four (68.5%) of the validation group had a clinical response to CRT, and 67 patients (62.0%) showed a volumetric response at 6 months (Table 2). RSDc was higher in responders than nonresponders (66±35% versus 38±24%; P<0.001) and correlated with LVESV reduction (r=−0.48; P<0.001). Using the derived cutoff value of 40%, RSDc predicted CRT response with a sensitivity of 89% (95% confidence interval, 79–84) and specificity of 84% (95% confidence interval, 69–95). This gave a positive predictive value of 84% and a negative predictive value of 85%. An RSDc >40% at baseline seemed to identify those with greater LV reverse remodeling after CRT (28±11% versus 9±8%; P<0.001).

All Patients

Relationship of RSD to QRS Duration and Heart Failure Pathogenesis

A great proportion of patients with nonischemic pathogenesis demonstrated remodeling response after CRT when compared with ischemic pathogenesis (68% versus 56%). Although patients with nonischemic and ischemic pathogeneses had similar baseline RSDc (60±36% versus 52±24%; P=0.1), RSDc(mid) was greater in CRT responders irrespective of pathogenesis (Figure 5). We examined the relationship between RSD, QRS duration, using a cutoff value of 150 milliseconds, and CRT remodeling response. RSDc was greater in CRT responders than nonresponders regardless of baseline QRS duration (Figure 5).
Follow-up survival data were available for all 210 patients over a mean length of 855±315 days; there were a total of 45 deaths (21%). In patients with a RSDc >40% (n=131), there were a total 17 deaths compared with 28 deaths in patients with an RSD of <40% (n=79). The presence of dysynchrony assessed by RSDc was associated with improved survival (P<0.001; Figure 6). Outcomes remained similar in each group when stratified according to baseline QRS duration (Figure 6).

**Discussion**

The present study assesses the use of a RSD dyssynchrony parameter to potentially enhance the selection of patients for CRT. The RSD is able to predict LV reverse remodeling with a higher sensitivity and specificity and has better correlation by guest on June 18, 2017 http://circimaging.ahajournals.org/ Downloaded from

### Table 2. Clinical and Echocardiographic Variables Between Responders and Nonresponders

<table>
<thead>
<tr>
<th>Characteristic (mean±SD)</th>
<th>Derivation Group (n=102)</th>
<th>Validation Group (n=108)</th>
<th>P Value</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NYHA class</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>3.1±0.3</td>
<td>3.2±0.3</td>
<td>0.30</td>
<td>3.1±0.3</td>
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<tr>
<td>Follow-up</td>
<td>1.8±0.8</td>
<td>2.9±1.0</td>
<td>&lt;0.001</td>
<td>1.9±0.8</td>
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<tr>
<td>% Change</td>
<td>36</td>
<td>12</td>
<td>0.001</td>
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<tr>
<td><strong>6-MWT, m</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>235±101</td>
<td>198±91</td>
<td>0.06</td>
<td>215±95</td>
</tr>
<tr>
<td>Follow-up</td>
<td>320±112</td>
<td>221±82</td>
<td>&lt;0.001</td>
<td>295±102</td>
</tr>
<tr>
<td>% Change</td>
<td>36</td>
<td>12</td>
<td>0.001</td>
<td></td>
</tr>
</tbody>
</table>

**Minnesota Living With Heart Failure Questionnaire**

<table>
<thead>
<tr>
<th>Characteristic (mean±SD)</th>
<th>Derivation Group (n=102)</th>
<th>Validation Group (n=108)</th>
<th>P Value</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>52±18</td>
<td>57±21</td>
<td>0.24</td>
<td>55±18</td>
</tr>
<tr>
<td>Follow-up</td>
<td>27±19</td>
<td>46±19</td>
<td>&lt;0.001</td>
<td>29±19</td>
</tr>
<tr>
<td>% Change</td>
<td>−48</td>
<td>−19</td>
<td>&lt;0.001</td>
<td>−47</td>
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**LVEDV**

<table>
<thead>
<tr>
<th>Characteristic (mean±SD)</th>
<th>Derivation Group (n=102)</th>
<th>Validation Group (n=108)</th>
<th>P Value</th>
<th>P Value</th>
</tr>
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<tbody>
<tr>
<td>Baseline</td>
<td>194±81</td>
<td>202±91</td>
<td>0.25</td>
<td>201±81</td>
</tr>
<tr>
<td>Follow-up</td>
<td>144±79</td>
<td>190±78</td>
<td>&lt;0.001</td>
<td>152±79</td>
</tr>
<tr>
<td>% Change</td>
<td>−26</td>
<td>−6</td>
<td>&lt;0.001</td>
<td>−24</td>
</tr>
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</table>

**LVEF, %**

<table>
<thead>
<tr>
<th>Characteristic (mean±SD)</th>
<th>Derivation Group (n=102)</th>
<th>Validation Group (n=108)</th>
<th>P Value</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>23±7</td>
<td>24±6</td>
<td>0.53</td>
<td>23±7</td>
</tr>
<tr>
<td>Follow-up</td>
<td>32±9</td>
<td>27±7</td>
<td>&lt;0.001</td>
<td>33±9</td>
</tr>
<tr>
<td>% Change</td>
<td>39</td>
<td>13</td>
<td>&lt;0.001</td>
<td>+43</td>
</tr>
</tbody>
</table>

LVEDV indicates left ventricular end-diastolic volume; LVEF, left ventricular ejection fraction; LVESV, left ventricular end-systolic volume; 6-MWT, 6-minute walk test; and NYHA, New York Heart Association.

### Table 3. Comparison of Dyssynchrony Parameters Between Responders and Nonresponders and ROC Analyses

<table>
<thead>
<tr>
<th>Dyssynchrony Parameter</th>
<th>Responders (mean±SD)</th>
<th>Nonresponders (mean±SD)</th>
<th>P Value</th>
<th>Cutoff Value</th>
<th>Area Under the Curve (ROC)</th>
<th>Sensitivity (95% CI), %</th>
<th>Specificity (95% CI), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSDc, %</td>
<td>74±39</td>
<td>29±15</td>
<td>&lt;0.001</td>
<td>40</td>
<td>0.91</td>
<td>87 (74–94)</td>
<td>88 (72–93)</td>
</tr>
<tr>
<td>Rs-SD12, ms</td>
<td>226±154</td>
<td>122±93</td>
<td>&lt;0.001</td>
<td>130</td>
<td>0.75</td>
<td>73 (57–92)</td>
<td>74 (52–94)</td>
</tr>
<tr>
<td>Ts-SD12, ms</td>
<td>144±100</td>
<td>100±58</td>
<td>&lt;0.001</td>
<td>122</td>
<td>0.71</td>
<td>69 (51–86)</td>
<td>68 (50–82)</td>
</tr>
<tr>
<td>Ts-SL, ms</td>
<td>70±31</td>
<td>60±26</td>
<td>0.17</td>
<td>65</td>
<td>0.65</td>
<td>61 (29–82)</td>
<td>59 (33–80)</td>
</tr>
<tr>
<td>IVMD, ms</td>
<td>39±12</td>
<td>34±11</td>
<td>0.12</td>
<td>33</td>
<td>0.59</td>
<td>58 (28–89)</td>
<td>61 (35–86)</td>
</tr>
</tbody>
</table>

AS-P indicates anteroseptal to posterior; CI, confidence interval; ROC, receiver-operating characteristic curve; Rs-SD12, SD of the time to peak strain of the 12 nonapical segments; RSDc, calculated radial strain delay; RSDc(mid), calculated radial strain delay (midmyocardial level only); Ts-SL, dysynchrony by tissue Doppler imaging determined as the maximal time difference in peak systolic velocities between the basal septum and the lateral segment; Ts-SD12, SD of the time to peak systolic velocity of the 12 nonapical segments; and IVMD, interventricular mechanical dyssynchrony.
with reduction of LVESV at 6 months than measures based on
the regional timing of either myocardial velocity or 2-dimen-
sional strain. Our findings suggest that a parameter incorpo-
rating both the regional timing and the amplitude of myocardial
deforestation is superior in predicting CRT response, including
LV reverse remodeling and survival, than parameters based on
timing alone. Similar predictive potential is seen in patients
regardless of underlying pathogenesis. These findings sup-
port the superiority of strain over velocity and demonstrate
additional refinement in CRT patient selection by inclusion of
measures of residual contraction.

A reduction of LVESV of >15% after CRT is associated
with improved prognosis16 but is not realized in ≈30% of all
heart failure patients undergoing device therapy. Mechanical
dysynchrony assessment using echocardiography may
enhance patient selection, and tissue velocity imaging of lon-
gitudinal wall motion is the most widely reported method.15,17
Unlike strain, velocity-based measures are unable to differ-
entiate active contraction from passive motion and have a
low specificity for patient selection. This is demonstrated in a
recent study by Miyazaki et al,18 who report that up to 68% of
normal individuals with normal LV function and normal QRS
duration have tissue velocity parameters that exceed the cut-
offs for recommending CRT implantation. When tissue strain
is used, however, there is minimal overlap between groups of
patients with and without left bundle-branch block, with and
without LV impairment. In the present study, both dyssyn-
chrony parameters based on tissue velocity (namely the Tv-SL
and Tv-SD12) were similar in responders and nonresponders.
Although this result is in conflict with the study by Yu et al,3
our findings are in line with more recent reports. Mele et al19
report a comparison of tissue myocardial strain and velocity
dysynchrony and found that strain-derived regional timing
of 12 nonapical segments better identified CRT responders.
Likewise, Porciani et al20 report a very low specificity of only
39% for the Tv-SD12 using a cutoff value of 33 milliseconds
to predict response at the 6-month follow-up.

Although strain seems to be superior to velocity, not all
strains are the same. Delgado et al21 in 242 CRT patients with
6-month follow-up showed that segmental timing of radial and
not longitudinal strain by speckle-tracking analysis predicted
response. We hypothesized that a strain-based approach,
although an advancement on velocity-based parameters,
still inherently fails to take into account residual contraction
by being limited only to the timing and not to the extent of
myocardial deformation. Myocardial viability assessed by
¹⁸F-fluorodeoxyglucose and positron emission tomography
predicts response with a sensitivity of 74% and a specificity
of 87%; similarly, extensive LV scar is associated with poor
outcomes after CRT.7,22 Speckle-tracking strain analysis has
been shown to correctly identify segmental LV dysfunction

Figure 3. Relationship between baseline calculated radial strain
delay (RSDc) and change in left ventricular end-systolic volume
(LVESV) change at 6 months.

Figure 4. Receiver-operating characteristic curve for the radial
strain delay. Area under the curve (AUC), sensitivities, and speci-
ficities are given for proposed cutoff values of 40%.

Figure 5. Radial strain delay (RSD) in cardiac resynchronization therapy (CRT)
responders (>15% reduction in left ventricular end-systolic volume) and nonre-
sponders according to pathogenesis and baseline QRS duration. ICM indicates
ischaemic cardiomyopathy and non ICM non ischaemic cardiomyopathy.
The RSDc is a parameter based on both these elements and is considered of the underlying myocardial substrate. On the highlights the limitations of a timing-based approach without where spherical geometry is often encountered. This study strain analysis, which unlike Doppler strain is less affected calculated in several ways; we elected to use speckle-tracking strain analysis, which unlike Doppler strain is less affected as a predictor of LV reverse remodeling. The authors report the use of a strain delay parameter based on speckle-tracking longitudinal motion of 16 myocardial segments and show a sensitivity of 91% and specificity of 90% for predicting the same prespecified end point as in this study. Furthermore, they have used this approach in a multicenter observational study of 189 CRT patients with analyzable echo data using they have used this approach in a multicenter observational study of 189 CRT patients with analyzable echo data using this predefined cutoff to predict response with a sensitivity of 92% and specificity of 65%.

The present study is the first to report the benefit of quantifying wasted energy as a marker of CRT response using speckle-tracking radial strain analysis. The RSDc can theoretically be calculated in several ways; we elected to use speckle-tracking strain analysis, which unlike Doppler strain is less affected by insonation angle, a particular concern in the failing heart where spherical geometry is often encountered. This study highlights the limitations of a timing-based approach without consideration of the underlying myocardial substrate. On the basis of this principle, Carasso et al report that the absence of passively compliant segments (defined as >5% holosystolic stretching) using longitudinal speckle strain analysis in a predominantly ischemic population predicts response with a sensitivity of 98% and specificity of 88%. The RSDc is just 1 possible method of incorporating elements of timing and residual contraction, but it is not the only one and may not be the most optimal technique. Because the move from velocity- to strain-based timing gathers momentum, this study provides further support, albeit in a small cohort, for an even further shift from the timing of regional strain alone to incorporate elements of strain amplitude.

**Limitations**

Although promising, the RSDc has been assessed in the present study in only a relatively small cohort of patients in a single center, and further investigation is warranted, in particular its use in patients with coronary artery disease. Validation with formal quantification of scar burden should be undertaken to clarify its use. The calculation of the RSDc was restricted to the 12 basal and midsegments in the radial vector because of a higher proportion of nonvalid tracking of the apical segments. A more comprehensive approach using 3D speckle tracking may yield better sensitivities and specificities. An automated software-based calculation of the RSDc may further widen the application of this method. Our current findings are restricted to patients with left bundle-branch block and may not be suitable for patients with a QRS of <120 milliseconds or with right bundle-branch block; this requires further assessment. Finally, we acknowledge that the use of a reduction in LVEF as a remodeling parameter to dichotomize the response to CRT alone has limitations and does not encompass both clinical and structural data that are included in a composite score.

**Conclusion**

A novel RSDc dyssynchrony parameter incorporating the timing and amplitude of dyssynchronous myocardial segmental motion may offer a reliable single measure to predict response to CRT with high sensitivity and specificity and is related to long-term survival.

**Acknowledgments**

We thank Addenbrooke’s Charitable Trust, Papworth Hospital Research and Development Department, and Cambridge Biomedical Research Center funded by the UK National Institute for Health Research for their support in conducting this work.

**Disclosures**

None.

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**CLINICAL PERSPECTIVE**

Characterization of the myocardium in patients with heart failure is important to enhance selection for cardiac resynchronization therapy (CRT). The ability of echocardiographic dyssynchrony parameters to predict CRT response based on segmental timing alone, which is independent of underlying contractility, has been disappointing. We report the ability of a derived speckle-tracking echocardiography radial strain delay (RSD) parameter, RSDc, to predict left ventricular remodeling after CRT in both a derivation and a validation cohort. RSDc was calculated as the net difference between peak and end-systolic strain, summed for each of the 12 basal and midmyocardial segments. It is designed to integrate both amplitude (a potential measure of contractility) and the timing of myocardial regional deformation to quantify the extent of wasted energy resulting from early and late segments with maximal deformation either before peak ejection or after aortic valve closure. RSDc thereby incorporates measures of left ventricular dysfunction that provide the substrate for CRT. For example, low-amplitude segments (scar) that do not contribute effectively to myocardial ejection (and are not recruitable by CRT) contribute little to the calculated RSDc. We propose that RSDc defines those with a greater degree of wasted energy and has the potential to predict the remodeling response to CRT in both ischemic and nonischemic heart failure. Further validation is required in a large prospective study to assess the use of RSDc to guide the use of CRT and to limit the number with a poor response to device therapy.
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_Circ Cardiovasc Imaging_. 2013;6:177-184; originally published online January 30, 2013;
doi: 10.1161/CIRCIMAGING.112.000191
_Circulation: Cardiovascular Imaging_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2013 American Heart Association, Inc. All rights reserved.
Print ISSN: 1941-9651. Online ISSN: 1942-0080

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