Analysis of Ventricular Activation Using Surface Electrocardiography to Predict Left Ventricular Reverse Volumetric Remodeling During Cardiac Resynchronization Therapy

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Background—Cardiac resynchronization therapy for heart failure with left bundle branch block reduces left ventricular (LV) conduction delay, contraction asynchrony, and LV end-systolic volume (“reverse remodeling”). Up to one third of patients do not improve, and the electric requirements for reverse remodeling are unclear. We hypothesized that reverse remodeling is predicted by the left bundle branch block ventricular activation sequence, the paced activation sequence, and interactions between these 2 conditions.

Methods and Results—Twelve-lead ECGs during left bundle branch block and cardiac resynchronization therapy were analyzed in 202 consecutive patients (New York Heart Association class III to IV heart failure, ejection fraction $\geq 35\%$) for predictors of reverse remodeling ($\geq 10\%$ reduction in end-systolic volume) at 6 months. Greater longest baseline LV activation time predicted increased odds of reverse remodeling (odds ratio [confidence interval] $1.30 [1.11, 1.52]$ per 10-ms increase), whereas higher QRS scores for LV scar predicted reduced reverse remodeling (odds ratio [confidence interval] $0.49 [0.27, 0.88]$ for each 1-point increase from 0 to 4; $0.92 [0.83, 1.01]$ for each 1-point increase $\geq 4$). After cardiac resynchronization therapy, increasing R amplitudes in leads V1 through V2 (odds ratio [confidence interval] $2.76 [1.01, 7.51]$ for each 1 increase over $\geq 4.5$) and left–right frontal axis shift (odds ratio [confidence interval] $2.00 [0.99, 4.02]$), indicators of ventricular activation wavefront fusion, were positive predictors of reverse remodeling. Predicted probability of reverse remodeling ranged from $<20\%$ for patients with adverse predictors to $99\%$ for those with positive predictors.

Conclusions—Ventricular activation with the use of the ECG accurately predicts LV reverse remodeling during cardiac resynchronization therapy. Greater longest baseline LV activation time and smaller scar volume combined with wavefront fusion on the paced ECG, anticipate higher probability of reverse remodeling. (Circulation. 2010;121:626-634.)

Key Words: bundle-branch block • implantable cardioverter-defibrillator • heart failure • pacing

We hypothesized that the volumetric reverse remodeling response to CRT can be predicted by the baseline LBBB ventricular activation sequence, the paced ventricular activation sequence, and the interaction between these 2 conditions.

Methods

We developed a predictive model to test the hypothesis that the probability of reverse volumetric remodeling could be accurately characterized by the ventricular activation pattern on the 12-lead surface ECG before and after CRT.

Study Sample

The study sample consisted of 202 consecutive patients with New York Heart Association class III to IV heart failure despite medical therapy, LVEF $\leq 35\%$, and LBBB (QRS duration [QRSd] $\geq 120$ ms; delayed intrinsicoid deflection in leads I, V5, V6 $\geq 50$ ms; broad

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The requisite conditions during which reversal of LV conduction delay results in reverse remodeling are unknown.
slurred R waves in I, aVL, V₅, and V₆; rS or QS waves in V₁ through V₃; ST-T wave vectors opposite the major QRS vector). Patients with right bundle branch block (RBBB), right ventricular (RV) pacing, or myocardial infarction ≤3 months previously were excluded. Simultaneous biventricular pacing was applied without exception for the first 6 months.

**Echocardiography and ECG**

Standard supine 12-lead ECGs (filter range, 0.15 to 100 Hz; AC filter, 60 Hz, 25 mm/s, 10 mm/mV) were obtained at baseline and before discharge. Echocardiograms were performed at baseline and after 6 months of CRT. Patients were imaged in the left lateral decubitus position with a commercially available system (Vingmed System Seven, General Electric–Vingmed, Milwaukee, Wis) with a 3.5-MHz transducer at a depth of 16 cm in conventional parasternal and apical views. Standard 2-dimensional and color Doppler data triggered to the QRS complex were saved in cine-loop format. LV end-systolic volume (ESV) and end-diastolic volume (EDV) were measured at the apical 2- and 4-chamber views; LVEF was calculated with the use of the biplane Simpson method. Interobserver and intraobserver reproducibility for LV volume measures were 90% and 96%, respectively.³

**ECG Analysis of Ventricular Activation**

ECGs were analyzed blinded to echocardiographic results. All measurements were made with the use of digital calipers at 200% magnification calibrated for paper speed 25 mm/s. Normal frontal plane axis was +90° to −30°, left axis deviation (LADEV) ≥−30° to −60°, right axis deviation (RADEV) ≥+90° to +90°. Right superior axis (RSA) was >180° to +90°; right inferior axis (RIA) >90° to 180°. "Incompletely" right superior axis (IRSA) was extreme LADEV (<−60° to +90°) with rS or QS complexes in the inferior leads and equiphasic QR in I (see below for QRS hieroglyphic framework). Axis quadrant shift was displacement of LBBB frontal plane axis by ≥±1 quadrant during CRT (eg, normal→LADEV, normal→RSA).

**QRS Hieroglyphic Framework for Ventricular Activation Pattern Comparisons**

The QRS complex in each lead before and after CRT was deconstructed into 4 possible waveform elements (R, S, Q, QS). Absolute amplitudes (mV) and durations (ms) of all elements of each QRS complex were used to characterize specific activation patterns (eg, R and S present, R=S amplitude, pattern=RS). Ventricular activation in each lead was characterized by 9 possible patterns or QRS hieroglyphs, as follows: (1) R; (2) RS (R+S); (3) Q; (4) QRS (Q+S); (5) QS; (6) QR (Q>R); (7) QR (Q>R>S); (8) QR (Q>S>R); and (9) QRS (all 3 waveforms present).

**Characterization of Ventricular Activation During LBBB**

Typical LBBB activation is registered as right (R)→left (L) (frontal plane), anterior (A)→posterior (P) (horizontal plane), and variable axis. This yields a QRS hieroglyphic signature with dominant positive forces in I, aVL (R, Rs); negative forces in aVR (QS); variable forces in II, III, AVF (Rs, Rs, R, QS); dominant negative forces in V₁ through V₃ (QS, QS); transition V₄ through V₆ (Rs→Rs, R); and dominant positive forces in V₇ through V₆ (R, Rs).

**QRS Notching**

LBBB is characterized by sequential ventricular activation (RV→LV)⁴ and registered as fragmented QRS complexes with RSR' configuration ("notch"). QRS notching was defined as ≥±1 notch in the R or S wave present in ≥±2 adjacent anterior, lateral, or inferior leads.⁴

**RV and LV Activation Time**

Because multiple notches in the R and S wave during LBBB may occur because of myocardial scar,⁶ the first notch was assumed to indicate the transition between RV and LV depolarization. Notching in the first 40 ms of the S wave in V₁ through V₃ was excluded because this indicates scar in the QRS score. RV activation time (RVAT) was measured as time (ms) between QRS onset and first notch in any of ≥±2 adjacent leads. LV activation time (LVAT) was QRSd−RVAT (ms).

For modeling purposes, the longest LVAT (LVATmax) recorded in any lead and region was used. A numeric relationship between QRSd and LVATmax was derived with the use of linear regression (LVATmax [ms] = −35.839 + 0.763 × QRSd [ms] + 0.000619 × QRSd [ms] × 2), permitting estimation of LVATmax in the absence of QRS notching (40 patients).

**Quantification of LV Scar**

Myocardial scar has been linked to reduced CRT response.³ ECG quantification of LV scar volume was calculated with the use of the Selvester QRS score for LBBB.⁷ The effects of scar on LBBB surface registration translate as specific QRS hieroglyphic signatures, manifest as unopposed rightward electric forces by infarct region: qR, QR, RS in I, aVL (anterior-superior); QR, QR, RS in I, V₁; rS in V₂ (apical); QR, QR, RS in II, aVF (inferior); QS→Rs, RS, or Rs in V₃ through V₆ (anterior-septal). Notching on the ascending limb of the S wave in V₁ through V₆ indicates posterolateral infarct.

**Evidence for Ventricular Activation Fusion During Biventricular Pacing**

Experimental models of LBBB demonstrate maximum improvement in LV pump function occurs when intra-LV electric asynchrony is minimized by wavefront fusion.¹ Wavefront opposition and reversal during biventricular pacing should yield ECG evidence of fusion, as follows: (1) expected change in frontal plane electric axis: normal or LADEV→RADEV; (2) expected changes in QRS hieroglyphic signatures: rightward forces emerge in leads with dominant leftward forces (R in I, aVL→qR, QR, QS); anterior forces emerge in leads with dominant posterior forces (eg, QS in V₁→Rs, RS, Rs; QS or Rs in V₂→RS, Rs, R; or Rs or RS in V₅→Rs or Rs; Rs); (3) an alternate way of characterizing evidence for ventricular fusion is using regional or global measures of CH, the change in R wave amplitude in the expected direction in Lateral (I, aVL) and Precordial leads (V₁-V₆) (CHRLP) before and after CRT.

Although LV pacing yields specific ventricular activation patterns generally in accordance with stimulation site, nearly identical ECG activation sequences may be registered at widely spaced sites,² and electric resynchronization during CRT correlates unpredictably with stimulation site because of conduction blocks.⁵ For these reasons, LV lead position was not relevant to this analysis.

**End Points**

The primary end point was LV reverse volumetric remodeling, defined as ≥±10% reduction in ESV at 6 months.³ Supplemental reverse remodeling end points, chosen to provide additional insights into the predictive model, were ≥±10% reduction in EDV (mechanistically similar measure of reverse remodeling) and ≥±30% reduction in ESV ("superresponse"²).

**Statistical Analysis**

For descriptive summaries, categorical variables are presented as n (%) and continuous variables as median (25th, 75th percentile).

Indices of change in R amplitude were generated by calculating, for each patient, the change in R amplitude for each lead from baseline to post-CRT, as a proportion of the baseline value. The postimplantation value was used in cases in which an R was absent at baseline and present postimplantation; a value of 1 was used in cases in which an R was present at baseline and absent postimplantation; and a value of 0 was used in cases in which both were absent. Change values were set to positive if the change was in the expected direction (decrease in I, aVL, and V₅ through V₆; increase in V₁ through V₃) and were negative otherwise. Leads II, III, and aVF had no expected direction and retained their calculated sign. These change values were then averaged across relevant leads for each
Evidence for Ventricular Activation Fusion During CRT

A rightward axis emerged in 67% of patients. However, a RSA was observed in only 58% and RIA in 9%. In contrast, 20% had LADEV or normal axis during CRT, and 12% had IRSA. Therefore, nearly one third of patients did not have evidence of ventricular fusion by frontal plane axis during CRT. Similarly, although ~90% had an axis quadrant shift, a RSA or RIA was achieved in only three fourths of these patients. The remaining one fourth had primarily a leftward (LADEV or IRSA) axis quadrant shift (Table 3).

Evidence for ventricular fusion with the use of QRS hieroglyphs was recorded in all 4 pivotal leads, with greatest frequency in I and V1. Evidence of wavefront collision (Q and S emergence, R regression) was observed in I for 71% of patients. However, total (QS) or near-total (Qr) reversal of activation in I was observed in only 55%. Similarly, total reversal of activation in V1 (dominant R emergence) was observed in only 50%. Evidence for activation reversal was ~50% less evident in aVL and V2.

**Table 3. Echocardiographic and ECG Variables at Baseline and Post-CRT**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Baseline Mean (25th, 75th percentile)</th>
<th>Post-CRT Mean (25th, 75th percentile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Echocardiographic measures</td>
<td>ESV, mL 157 (116, 199)</td>
<td>EDV, mL 207 (163, 252)</td>
</tr>
<tr>
<td></td>
<td>LVEF, % 25 (19, 30)</td>
<td></td>
</tr>
<tr>
<td>ECG measurements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atrial fibrillation, n (%)</td>
<td>23 (11)</td>
<td>14 (7)</td>
</tr>
<tr>
<td>QRSd, ms</td>
<td>165 (148, 176)</td>
<td>158 (142, 174)</td>
</tr>
<tr>
<td>Frontal plane axis, °</td>
<td>−31 (−51, −8)</td>
<td>−99 (−121, −76)</td>
</tr>
<tr>
<td>LADEV, n (%)</td>
<td>98 (49)</td>
<td>35 (17)</td>
</tr>
<tr>
<td>LVAT, ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inferior</td>
<td>109 (90, 130)</td>
<td></td>
</tr>
<tr>
<td>Lateral</td>
<td>100 (81, 116)</td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>103 (93, 129)</td>
<td></td>
</tr>
<tr>
<td>Maximum any region</td>
<td>113 (93, 129)</td>
<td></td>
</tr>
<tr>
<td>QRS score</td>
<td>6.0 (4.0, 9.0)</td>
<td>18 (12, 27)</td>
</tr>
<tr>
<td>% LV scar from QRS score</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

n=202 patients. Continuous variables are shown as median (25th, 75th percentile).
A ≥50% reduction in R-wave amplitude in I and aVL, reflecting L→R wavefront fusion in the horizontal plane, was observed in 60% of patients. Reciprocally, a ≥50% increase in R-wave amplitude in V1 and V2, due to A→P wavefront fusion, was observed in only 62%.

Predictors of ≥10% Reduction in ESV at 6 Months

A multivariable model identified 2 baseline and 2 post-CRT independent predictors of ≥10% reduction in ESV at 6 months (Table 4). Increasing LVAT\textsubscript{max} was associated with a greater probability of ≥10% reduction in ESV (OR [CI]=1.30 [1.11, 1.52] per 10-ms increase) up to 125 ms; for longer LVAT\textsubscript{max}, there was no further increase in probability of response (Figure 1). Patients with values in the lowest quartile (≥80 ms) had a 51% response rate compared with 73% response in patients with values of ≥125 ms. Although only 25 patients fell in this upper range, the response rate was 84% versus 60% in patients with mean change V1 through V2 R ≥4.5 times baseline. A second measure of ventricular fusion, LADEV→RADEV, was associated with increased probability of reverse remodeling (OR [CI]=2.00 [0.99, 4.02]). Patients showing this axis quadrant shift had a response rate of 70% compared with 60% in patients without.

Visual evidence for the effect of LVAT\textsubscript{max} and the other independent predictors of reverse remodeling is provided in Figure 1. Predicted probability of reverse remodeling is greatest for longer baseline LVAT\textsubscript{max} in the presence of post-CRT ventricular fusion, indicated by larger changes in R amplitude in leads V1 through V2 (top right) and LADEV→RADEV axis quadrant shift (lower left). In contrast, the positive effects of increasing LVAT\textsubscript{max} are offset by higher QRS scores such that longer LVAT\textsubscript{max} in the presence of a high QRS score has lower predicted probability of reverse remodeling than very short LVAT\textsubscript{max} in the presence of a low QRS score (lower right).

Predicting Reverse Remodeling Using a Global Measure of Ventricular Fusion

As for most of the R-wave amplitude directional change variables, there was no change in probability of reverse...
remodeling for the lowest values (Figure 2). Probability of reverse remodeling did not start to increase with larger CHRLP until post-CRT values were greater than baseline (OR [CI]=3.14 [0.97, 10.15] for each 1× increased >1; \( P=0.056 \)), whereas all patients with CHRLP \( <1 \) had equivalent probability of response, regardless of the actual CHRLP value.

### Tiers of Reverse Remodeling Response

Response tiers are shown in Table 5. The multivariable predictive model showed good discrimination (c-index 0.74). Low responders had \( \geq 1 \) adverse value for baseline predictors (ie, QRS score \( >17 \), LVAT\(_{\text{max}} \) \( <60 \) ms), or offsetting combinations (ie, QRS score 3 to 5+LVAT\(_{\text{max}} \) \( \leq 90 \) ms, or LVAT\(_{\text{max}} \) \( >110 \) ms+QRS score \( \geq 12 \)), or midrange values (ie, LVAT\(_{\text{max}} \) 90 to 110 ms, QRS score 6 to 11). Very short LVAT\(_{\text{max}} \) (48 to 62 ms) occurred only in this group, with no QRS scores 0 to 2. These patients also had limited or absent fusion evidence after CRT (Figure 3).

High responders had \( \geq 1 \) favorable predictor (ie, QRS score \( <3 \) or change in R amplitude \( >5 \)) or a combination of favorable predictors (ie, QRS score 3 and LVAT\(_{\text{max}} \) \( >110 \) ms, or QRS score 4 to 9 and LVAT\(_{\text{max}} \) \( >110 \) ms and quadrant shift). Alternately, high responders had fair values for 1 predictor that were offset by very favorable values for others (ie, smaller change in R amplitude but LVAT\(_{\text{max}} \) \( >130 \) ms). There were no QRS scores \( >12 \), whereas all changes in R amplitude \( >5 \) occurred in the high responders (Figure 3).

Middle-range responders had intermediate values for predictors (ie, LVAT\(_{\text{max}} \) 90 to 110 ms, QRS score 6 to 11, quadrant shift, midrange change in R amplitude) or an offsetting combination of very favorable and midrange predictor values (ie, long LVAT\(_{\text{max}} \) but high QRS score and small change in R amplitude).

### Predictors of Supplemental Reverse Remodeling End Points

Multivariable models for supplemental reverse remodeling end points yielded predictors similar to those in the \( \geq 10\% \) ESV reduction model (Table 6). The \( \geq 30\% \) ESV reduction end point was met by 59 patients (29.2%). Each 10-ms increase in LVAT\(_{\text{max}} \) was associated with increased probability of \( \geq 30\% \) ESV reduction, slightly less versus the \( \geq 10\% \) ESV model (OR=1.23 versus 1.30). The relationship of QRS score, for its entire range, to a \( \geq 30\% \) reduction in ESV was similar to the relationship of QRS score \( >4 \) to a \( \geq 10\% \) reduction in ESV (OR=0.91 versus 0.92 for each 1-point increase). Ventricular fusion (\( V_2 \) R amplitude change from \( <1 \) to \( >5 \) mm) also predicted \( \geq 30\% \) ESV reduction, similar to the relationship of QRS score \( >4 \) to a \( \geq 10\% \) reduction in ESV (OR=2.90). Axis quadrant shift was not significant, possibly because of the lower event rate.

The \( \geq 10\% \) EDV reduction end point was met by 45.5% of patients (92/202). Greater LVAT\(_{\text{max}} \) was directly associated with EDV reduction (OR=1.92 for each 10-ms increase up to 95), whereas higher QRS scores were inversely related.

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### Table 3. Evidence for Ventricular Activation Fusion During Simultaneous Biventricular Pacing

<table>
<thead>
<tr>
<th>Activation wavefront reversal in pivotal leads</th>
<th>Variables</th>
<th>Median (IQR)</th>
<th>( P ) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal plane electric axis</td>
<td>I: O emergence, S emergence, R regression</td>
<td>144 (71.3)</td>
<td>0.0010</td>
</tr>
<tr>
<td></td>
<td>R, Rs, rS, RS—QS</td>
<td>104 (51.5)</td>
<td>0.0022*</td>
</tr>
<tr>
<td></td>
<td>R, Rs, rS, RS—Qr</td>
<td>8 (4.0)</td>
<td>0.0010</td>
</tr>
<tr>
<td></td>
<td>R, Rs, rS, RS—qR</td>
<td>21 (10.4)</td>
<td>0.0010</td>
</tr>
<tr>
<td></td>
<td>R, Rs, rS, RS—QR</td>
<td>11 (5.4)</td>
<td>0.0010</td>
</tr>
<tr>
<td>RAVL: Q emergence, S emergence, R regression</td>
<td>R, Rs, rS, RS—QS</td>
<td>27 (13.4)</td>
<td>0.0010</td>
</tr>
<tr>
<td></td>
<td>R, Rs, rS, RS—Qr</td>
<td>4 (2.0)</td>
<td>0.0010</td>
</tr>
<tr>
<td></td>
<td>R, Rs, rS, RS—qR</td>
<td>24 (11.9)</td>
<td>0.0010</td>
</tr>
<tr>
<td></td>
<td>R, Rs, rS, RS—QR</td>
<td>4 (2.0)</td>
<td>0.0010</td>
</tr>
<tr>
<td>V1: R emergence, QS regression</td>
<td>QS or rS—R, Rs, RS</td>
<td>100 (49.5)</td>
<td>0.0010</td>
</tr>
<tr>
<td>V2: R emergence, QS or rS regression</td>
<td>QS or rS—R, Rs, RS</td>
<td>48 (23.8)</td>
<td>0.0010</td>
</tr>
<tr>
<td>Mean R amplitude change ( \leq 50% ) in expected direction for pivotal leads</td>
<td>I and aVL</td>
<td>121 (59.9)</td>
<td>0.0010</td>
</tr>
<tr>
<td></td>
<td>V1 and V2</td>
<td>100 (49.5)</td>
<td>0.0010</td>
</tr>
</tbody>
</table>

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### Table 4. Multivariable Model for Predictors of \( \geq 10\% \) Reduction in ESV

<table>
<thead>
<tr>
<th>Variable</th>
<th>OR (95% CI) for ESV Reduction</th>
<th>( P ) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LVAT(_{\text{max}} ) increase up to 125</td>
<td>1.30 (1.11, 1.52)</td>
<td>0.0010</td>
</tr>
<tr>
<td>QRS score</td>
<td>0.49 (0.27, 0.88) for each 1-point increase from 0 to 4</td>
<td>0.0022*</td>
</tr>
<tr>
<td></td>
<td>0.92 (0.83, 1.01) for each 1-point increase &gt;4</td>
<td></td>
</tr>
<tr>
<td>Post-CRT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean change in R amplitude in V1 and V2 in expected direction</td>
<td>2.76 (1.01, 7.51) for each 1-mV increase &gt;4.5</td>
<td>0.048</td>
</tr>
<tr>
<td>LADEV to RADEV</td>
<td>2.00 (0.99, 4.02)</td>
<td>0.052</td>
</tr>
</tbody>
</table>

Model c-index=0.74. *Overall test.
Ventricular fusion (V1R amplitude change from 0 to 5 mm) also predicted EDV reduction (OR=3.03); axis quadrant shift did not.

Discussion
This study demonstrates that the probability of reverse volumetric LV remodeling during CRT in patients with asynchrony heart failure and LBBB can be accurately predicted by characterization of the ventricular activation sequence before and after CRT with the use of the standard 12-lead ECG. The main findings are as follows: (1) The translational mechanism for volumetric reverse remodeling is activation wavefront fusion, which is evident on the paced ECG; and (2) the probability of reverse remodeling is

Figure 1. Probability of reverse remodeling by baseline and post-CRT predictors. Top left, Increasing probability of response with greater LVAT\text{max}. Line represents predicted probability of response for each value of LVAT\text{max}. Diamonds represent actual response rates among LVAT\text{max} quartiles. Top right, Increasing probability of response with greater LVAT\text{max} and post-CRT evidence of ventricular fusion (P→A activation reversal). Bottom left, Increasing probability of response with greater LVAT\text{max} and post-CRT evidence of ventricular fusion (L→R activation reversal). Bottom right, Increases in QRS score reduce response probability for any value of LVAT\text{max}.

Figure 2. Predicting reverse remodeling using a global measure of ventricular fusion. Greater changes in R-wave amplitudes after CRT, indicative of wavefront fusion, predict higher probability of response. The points along the line are individual predicted values.

This point represents 138 pts with mean R change values ≤ 1, all of whom have equivalent probability of response.
positively influenced by LV conduction delay (LVAT\textsubscript{max}) and negatively influenced by LV scar volume (QRS score) on the baseline ECG.

Uncertainty about the physiology of ventricular resynchronization is reflected in significant heterogeneity in clinical response to CRT. A CRT responder feels better, has less heart failure morbidity, and demonstrates evidence of reverse remodeling; a nonresponder exhibits none of these. Up to one third of CRT patients are nonresponders. The reasons for this are complex and incompletely characterized but most likely relate to poorly understood interactions between substrate conditions and pacing-induced changes in ventricular activation.

We evaluated reverse volumetric remodeling as an end point because (1) experimental models have demonstrated a direct linkage between LV electric activation, mechanics, and reverse remodeling\textsuperscript{1,10}; (2) reverse remodeling is associated with reduced heart failure morbidity and mortality\textsuperscript{2}; and (3) it is the least subjective element of CRT response.

At baseline, longer LVAT\textsubscript{max} was significantly associated with ESV reduction, indicating that greater LV conduction delay is associated with higher probability of reverse remodeling, if it is assumed that delay is sufficiently corrected by CRT. In contrast, each QRS score point (indicative of 3% LV scar volume) was associated with a reduction in the probability of reverse remodeling, with the greatest effect in the lower points range (0 to 4). Higher LV scar volume is associated with lower probability of reverse remodeling. After CRT, larger changes in R-wave amplitude in pivotal leads \( V_1 \) through \( V_2 \), indicating P->A activation reversal, and LADEV->RADEV frontal plane axis quadrant shift, indicating L->R activation reversal, were associated with an increased probability of reverse remodeling. Higher CHRLP scores, a global measure of change in ventricular activation during CRT, also predicted ESV reduction. Therefore, paced ventricular activation wavefront fusion increases the probability of reverse remodeling. These results provide evidence that interactions between myocardial substrate (scar volume), baseline LV conduction delay, and paced-activation wave-

<table>
<thead>
<tr>
<th>Tier</th>
<th>n</th>
<th>Range of Predicted Probability, %</th>
<th>Mean Predicted Probability, %</th>
<th>Actual Response Rate, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low response</td>
<td>56</td>
<td>0 to &lt;50</td>
<td>39</td>
<td>41</td>
</tr>
<tr>
<td>Middle response</td>
<td>88</td>
<td>50 to &lt;75</td>
<td>63</td>
<td>61</td>
</tr>
<tr>
<td>High response</td>
<td>58</td>
<td>75 to 100</td>
<td>88</td>
<td>88</td>
</tr>
</tbody>
</table>

Table 5. Predicted Probabilities of Low, Middle, and High Responders

Figure 3. Top, High responder, baseline: LVAT\textsubscript{max} = 142.7 ms, QRS score = 1. Determination of RVAT\textsubscript{max} with the use of QRS notching, present in 2 regions, is shown at the bottom. Time between QRS onset (first arrow) and notch nadir (second arrow) is RVAT. Shortest RVAT\textsubscript{max} = 45.3 ms, LVAT\textsubscript{max} = QRSd (188 ms) – 45.3 ms = 142.7 ms. Post-CRT: LADEV->RADEV=yes (L->R activation reversal, indicated by R->QS in I, R->qR in aVL), change in R in \( V_1 \) through \( V_2 \); 4.8 (P->A activation reversal, indicated by QS->R in \( V_1 \), QS->S in \( V_2 \)). Predicted probability of response = 0.9. Actual change in ESV = -24\%. Bottom, Low responder, baseline: LVAT\textsubscript{max} = 48.2 ms, QRS score = 14, by anatomic region: anterosuperior (ASUP), anteroseptal (AS), apical (AP), inferior (INF) and posterolateral (PL) walls. Post-CRT: LADEV->RADEV=yes (L->R activation reversal, indicated by R->QS in I, qR->QS in aVL), change in R in \( V_1 \) through \( V_2 \) = 0 (incomplete P->A activation reversal, indicated by QS->S in \( V_1 \), rS->QS in \( V_2 \)). Predicted probability of response = 0.21. Actual change in ESV = +29\%. Pt indicates QRS score point.
of LVAT\textsubscript{max}, the probability of reverse remodeling was still between substrate conditions and post-CRT evidence of paced fusion. Several other observations on the interaction delays, small scar volumes, and the most robust evidence of paced fusion. Those “volumetric superresponders” are characterized by large conduc-
tion delay, despite biventricular pacing, contributes signif-
icantly to volumetric nonresponse. Nearly 20% of patients had axis quadrant shift or low-range increases in V\textsubscript{1} through V\textsubscript{2} R amplitudes). Reciprocally, for very low values of LVAT\textsubscript{max}, the probability of reverse remodeling may still reach 80% if there is strong paced ECG evidence for ventricular fusion (ie, highest range increases in V\textsubscript{1} through V\textsubscript{2} R amplitudes).

Only two thirds of patients had paced ECG evidence of ventricular fusion. This implies that failure to correct LV conduction delay, despite biventricular pacing, contributes significantly to volumetric nonresponse. Nearly 20% of patients had axis quadrant shift to LAD\textsubscript{E}V\textsubscript{R} or IRSA (extreme LAD\textsubscript{E}V\textsubscript{R}), and 10% had a normal axis during CRT. In some of these patients, failure to generate ECG evidence of fusion during simultaneous biventricular pacing was likely due to LV capture latency, conduction delay, or blocks,\textsuperscript{4,5} with a common conse-
quence of different bidirectional paced activation times favoring persistent R→L, A→P conduction. Sequential biventricular pacing might improve the fusion response in some of these patients, especially the subset with IRSA. It is also likely that fusion failure in some patients was due to stimulation from a site incapable of reversing LV activation.

On the other hand, the probability of volumetric reverse remodeling was reasonably high in some patients even without paced ECG evidence of ventricular fusion. Global ventricular activation patterns are represented by the 12-lead ECG, whereas local activation patterns may be concealed.\textsuperscript{6} Reduction of local conduction delay sufficient to improve regional LV mechanics may be concealed within the surface registration of the paced ECG; alternately, concealed local activation patterns may prevent LV electric resynchronization. Because the translation of cardiac electric activation to the surface ECG is incompletely understood, interpretation of ventricular activation with the use of any surface method may be unpredictably incorrect.

This study supports the concept that asynchronous heart failure is fundamentally an electric disorder that can be resolved at the level of ventricular conduction. A close linkage between electric and mechanical asynchrony has been demonstrated in animal models\textsuperscript{11} and preliminarily in humans.\textsuperscript{12} The greater the LV conduction delay, the greater are the potential gains in reverse remodeling when conduction delay is sufficiently corrected, if it is assumed that LV scar volume is not prohibitive. Targeting LV pacing sites with the use of real-time ECGs to evaluate evidence of activation wavefront fusion and reversal, rather than rigid adherence to anatomic targets, may improve CRT response.

**Limitations**

Echocardiographic measures of LV volumes may be less accurate than other methods. The surface ECG may not accurately reflect important changes in LV activation. QRS score is modestly less accurate than newer imaging methods for calculating scar volume. We did not evaluate other forms of ventricular conduction delay.

**Conclusions**

Ventricular activation on the surface ECG accurately predicts ventricular reverse remodeling during CRT. Greater LVAT\textsubscript{max} and smaller scar volume on the baseline LBBB ECG, combined with wavefront fusion on the paced ECG, are associated with higher probability of ESV reduction.

**Disclosures**

Dr. Sweeney is a consultant to and has received honoraria for speaking from Medtronic Inc. Dr. Schalij has received grants from Biotronik, Medtronic Inc, and Boston Scientific. Dr. Bax has received grants from Biotronik, Medtronic Inc, Boston Scientific, BMS Medical Imaging, St Jude Medical, Edwards Life Sciences, and GE Healthcare. The remaining authors report no conflicts.

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**CLINICAL PERSPECTIVE**

Ventricular conduction delay due to left bundle branch block alters the left ventricular (LV) electric activation sequence. The resulting electric asynchrony is manifest in prolonged QRS durations due to slow myocardial conduction. This causes regional heterogeneity in contraction and stretch (mechanical asynchrony) that reduces pump function and stimulates negative LV reverse remodeling, indicated by increased LV volumes. The conceptual basis of cardiac resynchronization therapy (CRT) for asynchronous heart failure is to minimize LV conduction delay, which reduces contractile asynchrony and instantaneously improves LV mechanics. Sustained resynchronization of electromechanical activation induces “reverse” remodeling (LV volume reductions) and improved pump function (increased LV ejection fraction). Reverse LV remodeling is associated with reduced heart failure morbidity and mortality. Up to one third of CRT patients do not improve. The reasons for this are complex and incompletely characterized but can be explained by interactions between substrate conditions and pacing-induced changes in ventricular activation derived from analysis of the standard 12-lead ECG before and after CRT. Longer LV activation time and smaller LV scar volume during left bundle branch block on the baseline ECG predict higher probability of reverse remodeling. Evidence for activation wavefront fusion on the CRT-paced ECG, indicating conduction defect reversal, also predicts reverse remodeling and provides the translational mechanism for volumetric reverse remodeling. Knowledgeable application of the standard 12-lead ECG can be used to accurately predict the probability of a reverse remodeling response to CRT.

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Analysis of Ventricular Activation Using Surface Electrocardiography to Predict Left Ventricular Reverse Volumetric Remodeling During Cardiac Resynchronization Therapy
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