Cardiac Sympathetic Reserve and Response
to Cardiac Resynchronization Therapy

Cha et al: Sympathetic Function and Cardiac Resynchronization

Yong-Mei Cha, MD
Panithaya Chareonthaitawee, MD
Ying-Xue Dong, MD, PhD
Bradley J. Kemp, PhD
Jae K. Oh, MD
Chinami Miyazaki, MD
David L. Hayes, MD
Robert F. Rea, MD
Samuel J. Asirvatham, MD
Tracy L. Webster, RN
Connie M. Dalzell, RN
David O. Hodge, MS
Regina M. Herges, BS
Yan-zhong Yong, MD
Yanhua Zhang, MD
Peng-Sheng Chen, MD

Division of Cardiovascular Diseases (Drs Cha, Chareonthaitawee, Oh, Miyazaki, Hayes, Rea, and Asirvatham, and Mss Webster and Dalzell), the Department of Radiology, (Dr Kemp), and the Division of Biomedical Statistics and Informatics (Mr Hodge and Ms Herges), Mayo Clinic, Rochester, Minnesota., USA; the Department of Cardiology (Drs Dong and Yong), the First Affiliated Hospital of Dalian Medical University, Dalian, Liaoning, China; and the Krannert Institute of Cardiology (Drs Zhang and Chen), Indiana University School of Medicine, Indianapolis, Indiana.

Correspondence to:
Yong-Mei Cha, MD
Division of Cardiovascular Diseases, Mayo Clinic
200 First St SW
Rochester, MN 55905
Fax: 507-255-2550
Tel: 507-255-2502
Email: ycha@mayo.edu

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Abstract

**Background**—The objective of the study was to investigate the effect of cardiac resynchronization therapy (CRT) on cardiac autonomic function.

**Methods and Results**—This prospective study included 45 consecutive patients with heart failure who received CRT devices with defibrillator and 20 age-matched healthy controls. At baseline, 3 months and 6 months after CRT, we assessed New York Heart Association (NYHA) class, 6-minute walk distance, plasma sympathetic biomarker nerve growth factor, echocardiography, heart rate variability and cardiac presynaptic sympathetic function determined by iodine 123 metaiodobenzylguanidine scintigraphy. After CRT, NYHA class improved by 1 class (p<0.001), and left ventricular (LV) ejection fraction increased by 8% (p<0.001). Along with improvement in the standard deviation of all normal-to-normal R-R intervals (85.63±31.66 vs 114.79±38.99 milliseconds; p=0.004) and the standard deviation of the averaged normal-to-normal R-R intervals (82.62±23.03 vs 100.50±34.87 milliseconds; p=0.004), the delayed heart/mediastinum (H/M) ratio increased (1.82 [0.58] vs 1.97 [0.59]; p=0.03), whereas the mean (SD) H/M washout rate was reduced (48% [19%] vs 37% [22%]; p=0.01). Twenty-two of 45 study patients responded to CRT with a reduction of LV end-systolic volume index greater than 15%. Compared with nonresponders, responders had a higher delayed H/M ratio (2.11 vs 1.48; p=0.003), and lower H/M washout rate (37% vs 62%; p=0.003) at baseline.

**Conclusions**—CRT improved sympathetic function. Cardiac sympathetic reserve may be a marker for the reversibility of failing myocardial function.

**Key Words:** cardiac resynchronization therapy; heart failure; nerve growth factor; sympathetic nerve; metaiodobenzylguanidine iodine 123.
Abbreviations

CRT, cardiac resynchronization therapy
CRT-D, cardiac resynchronization therapy device with defibrillator
ECG, electrocardiogram, electrocardiographic
HF, heart failure
H/M, heart/mediastinum
$^{123}$I-MIBG, iodine 123 metaiodobenzylguanidine
LV, left ventricle, left ventricular
LVEF, left ventricular ejection fraction
LVESV, left ventricular end-systolic volume
NGF, nerve growth factor
NYHA, New York Heart Association
SDANN, standard deviation of the average normal-to-normal R-R intervals in all 5-minute segments
SDNN, standard deviation of all normal-to-normal R-R intervals
Cardiac resynchronization is an effective therapy in improving symptoms, quality of life, and survival in patients with advanced heart failure (HF) by correction of biventricular electrical and mechanical dyssynchrony caused by severe dilated cardiomyopathy.1–6 HF is associated with an abnormally activated sympathetic nervous system, attenuated cardiovascular reflexes, and downregulation of adrenergic nerve terminals.7, 8 The role of cardiac resynchronization therapy (CRT) in neurohormonal regulation of cardiac chronotropic and inotropic activity has not been well characterized. Nerve growth factor (NGF) is a neurotrophin with a pivotal role in the differentiation, maturation, and survival of sympathetic innervation.9 One study showed a marked reduction of circulating NGF levels and local cardiac NGF production that may be an adaptive response to sympathetic overactivity in HF.10 Recently, several radiolabeled compounds have been used for noninvasive imaging of cardiac neuronal function. The catecholamine analogue iodine 123 metaiodobenzylguanidine (123I-MIBG) is the tracer most commonly used to map myocardial presynaptic sympathetic innervation and activity.11–13 In this study, we aimed to examine the effect of CRT on neurohormonal integrity by studying plasma levels of NGF, and cardiac presynaptic sympathetic function, as determined by nuclear cardiac imaging modalities (123I-MIBG scintigraphy), in patients with HF who received CRT.

Methods
The study was approved by the Mayo Institutional Review Board. Written informed consent was obtained from each study subject.

Study Patients
From January 1, 2005, through June 30, 2008, 45 consecutive patients with advanced HF at Mayo Clinic (Rochester, Minnesota) were enrolled in the study. All met clinical criteria for CRT (left ventricular ejection fraction [LVEF] ≤35%, New York Heart Association [NYHA] functional class III or IV, QRS duration ≥120 milliseconds). Patients also met criteria for an implantable cardioverter defibrillator for primary or secondary sudden death prevention. All
patients received a cardiac resynchronization therapy device with defibrillator (CRT-D). Twenty age-matched healthy volunteers without evidence of structural heart disease served as control subjects.

**Clinical Evaluation Before CRT**

Before device implantation, each enrolled subject underwent clinical evaluation to determine NYHA functional class and medication use; a 12-lead electrocardiographic (ECG) evaluation was performed. Exercise capacity was assessed by a 6-minute walk. Cardiac structure and function were assessed using transthoracic echocardiography. Peripheral venous blood samples were collected to measure plasma NGF levels. Cardiac autonomic function was assessed using 24-hour ambulatory ECG monitoring. Presynaptic cardiac sympathetic activity was determined by $^{123}$I-MIBG scintigraphy ($n=24$). Normal control subjects underwent echocardiographic examination to exclude structural heart diseases. (Details about echocardiography, 24-hour ambulatory ECG monitoring, plasma NGF level, and $^{123}$I-MIBG scintigraphy, are described in the online supplement.)

**CRT-D Implantation and Patient Follow-Up**

Clinically available CRT-D devices and leads were used. The right ventricular lead was positioned in the right ventricular apex. The desired position for left ventricular (LV) lead placement was prioritized as follows: lateral/posterolateral, anterior lateral, anterointerventricular, or middle cardiac veins. The standard device settings included atrioventricular delay of 100 milliseconds (sensed) and 130 milliseconds (paced), with DDD or DDDDR mode and standard lower and upper pacing rates (50 and 120-130 beats/minute, respectively).

All patients (and control subjects) returned for follow-up at 3 and 6 months after CRT implantation. Patients underwent NYHA class and 6-minute walk reassessment, repeated blood
tests for plasma NGF levels, and underwent 24-hour ambulatory ECG monitoring and an echocardiography study at 3 and 6 months follow-up. The percentages of biventricular pacing, as well as appropriate or inappropriate antiarrhythmic therapy for sustained ventricular tachyarrhythmia, were determined. The follow-up cardiac $^{123}$I-MIBG scintigraphy was performed only at the 6-month follow-up. The further follow-up information after 6 months, including death, heart transplantation, LV assisted device implantation, NYHA class and echocardiographic reassessment were ascertained through the electronic medical records.

**Definition of Response to CRT**
Reverse remodeling of the LV with CRT was predefined as a 15% or greater reduction in LV end-systolic volume (LVESV) at follow-up.\textsuperscript{14-16} Patients who died before the 6-month follow-up were considered nonresponders.

**Data and Statistical Analysis**
All imaging results were obtained by blinded reading. The data was interpreted by cardiologists who were masked to the patients’ clinical status. Data are presented as mean (SD) or median (Q1, Q3). The Student $t$ test was used to compare continuous factors between patients with HF and control subjects. The Fisher exact test was used to compare categorical variables. Values obtained before and after CRT were compared with a paired $t$ test if the data were normally distributed. A Wilcoxon signed rank test was used if the data were nonnormally distributed. The Pearson or Spearman correlation coefficient was used to determine the association between the continuous factors and the change of clinical outcome responses to CRT. $P$ values less than .05 were considered statistically significant.

**Results**

**Baseline Patient Characteristics**
Baseline characteristics of the patients and control subjects are shown in Table 1. Most patients
receiving CRT were male. As expected, patients with HF had a shorter 6-minute walk distance (p<0.001), significantly larger LV end-diastolic and LVESV index (p<0.001 for both), impaired LVEF (p<0.001), and elevated pulmonary artery systolic pressure (p<0.001) compared with control subjects. The interventricular and intraventricular dyssynchrony (by strain only) were present in the CRT group. The standard deviation of all normal-to-normal (SDNN) R-R intervals (p=0.009) and standard deviation of the average normal-to-normal (SDANN) R-R intervals in all 5-minute segments (p=0.005) in the CRT group were significantly lower than those of the control group. The baseline delayed MIBG heart/mediastinum (H/M) ratio was significantly lower (p<0.001) but the H/M washout rate was significantly higher (p=0.001) in patients with HF compared with controls. Most patients with HF were taking angiotensin-converting enzyme or angiotensin receptor–blocking agents (87%), β-blockers (91%), and statins (64%).

**Effect of CRT on Sympathetic Function**

Forty-three patients completed 6 months of follow-up. One patient died of end-stage HF and another of ventricular tachyarrhythmia before completion of follow-up. All patients had stable medication use. Biventricular pacing was achieved in 95%±7% of the pacing time. Five patients (11%) had a total of 6 episodes of sustained ventricular tachycardia that was treated successfully by antitachycardia pacing or defibrillation (or both) within 6 months after receiving the CRT-D.

Table 2 shows the effects of CRT at the 3- and 6-month follow-ups. NYHA class, distance of 6-min walk and echocardiographic parameters were improved 3 months after CRT, and sustained or further improved at 6 months. At the 6-month follow-up, NYHA class improved by approximately 1 class (p<0.001). The mean improvement in LVEF was 8% (p<0.001), and the LVESV index was reduced by 15% (p<0.001). The heart rate variability after CRT, as determined by SDNN (p=0.004) and SDANN (p=0.004), was improved. The delayed H/M ratio was increased (p=0.03), while the H/M washout rate was reduced (improved, p=0.01) overall. Of
24 patients who had $^{123}$I-MIBG studies, 13 (54%) showed improvement in delayed H/M ratio and/or H/M washout rate (≥ 10% change compared to baseline) 6 months after CRT.

Of our cohort, 35 patients had continued clinical follow-up after 6 months at our institution. The improvements in NYHA class (2.0 [2.0, 3.0] vs. baseline 3.0 [3.0, 3.0], p<0.001) and LVEF (30.7±14.0 vs. baseline 25.8 ±5.3%, p<0.001) were sustained during a mean follow-up duration of 36±16 months.

**CRT Response**

Overall, 22 of 45 study patients had a reduction in LVESV index of at least 15%. Most patients with nonischemic cardiomyopathy responded to CRT (65%), but the response rate was lower for patients with ischemic cardiomyopathy (32%; p=0.03). Before CRT, responders had longer 6-minute walk distance (387 vs 320 m; p=0.03), wider QRS complex (166 vs 146 milliseconds; p=0.01), greater interventricular conduction delay (47 vs 28 milliseconds, p=0.005), and intraventricular dyssynchrony (123 vs 87 milliseconds; p=0.005, Figure 1A). Of 24 patients who had $^{123}$I-MIBG studies and LVESV index measures, responders had a higher baseline delayed H/M ratio (2.11 vs 1.48; p=0.003), and lower H/M washout rate (37% vs 62%; p=0.003), compared with nonresponders (Figure 1B). No differences were observed between responder and nonresponder groups for baseline NYHA class, LVEF, LVESV index, NGF level, or SDNN and SDANN values.

Several factors, determined at baseline, were significantly correlated with changes in the LVESV index after CRT; specifically, these included distance of the 6-minute walk ($r=−0.36$; p=0.02), interventricular conduction delay ($r=−0.47$; p=0.002), and intraventricular dyssynchrony averaged over 12 LV segments ($r=−0.63$; p<0.001). Of 24 patients who had $^{123}$I-MIBG studies, the changes in the LVESV index after CRT were significantly correlated with delayed H/M ratio ($r=−.42$; p=0.048; Figure 2A), and H/M washout rate ($r=0.45$; p=0.03; Figure 2B). Decreased
123I-MIBG uptake and higher H/M washout rates at baseline were associated with a nonresponse after CRT. The other baseline variables were not correlated with improvement in LVESV index.

CRT significantly improved delayed H/M ratio (from 2.04 to 2.30; \( p=0.04 \)) and H/M washout rate (from 39% to 21%; \( p=0.004 \)) in responders only (nonresponder delayed H/M ratio changed from 1.49 to 1.57 \( p=0.59 \) and H/M washout rate changed from 61% to 56% \( p=0.54 \)).

Response to CRT and Prognosis

Two patients died during the 6-month follow-up period. An additional 11 events occurred more than 6 months after CRT, during a mean period of 36 months after CRT-D implantation. These events included 6 deaths, 2 heart transplantations, and 3 LV assist device implantations. Of the total 13 death, transplant, and LVAD events, affected patients included 3 responders and 10 nonresponders \( p=0.02 \).

Discussion

Main Findings

Our study found CRT reverses cardiac autonomic remodeling by upregulating presynaptic receptor function as evidenced by increased 123I-MIBG H/M ratio and attenuated H/M washout rate, with concomitantly improved heart rate variability. The baseline cardiac sympathetic reserve, assessed by 123I-MIBG scintigraphy, may be a potential marker of clinical response to CRT.

Cardiac Autonomic Remodeling in HF

HF is associated with abnormally activated sympathetic and altered parasympathetic tone, attenuated cardiovascular reflexes, and maladaptive downregulation of adrenergic nerve terminals.7, 8 The attenuated heart rate variability, as observed in this study, conferred a dysregulation of heightened sympathetic tone and weakened parasympathetic outflow.17-20
However, the plasma NGF concentrations did not differ among patients with HF and control subjects. This result differed from findings previously reported by Kaye et al.\textsuperscript{10} who described reduced plasma NGF concentration in patients with HF. In their study, patients had severe HF, with a mean LVEF of 17%. Our patients were receiving optimal medical therapy and had a comparatively higher average LVEF. The circulating NGF level may be modulated after HF treatment to mask the degree of sympathetic dysregulation.\textsuperscript{21}

Cardiac adrenergic control is governed by sympathetic transmitter norepinephrine that is synthesized within neurons and released to the synaptic cleft. Most norepinephrine undergoes reuptake into presynaptic nerve terminals through the uptake-1 pathway.\textsuperscript{123}I-MiBG, the radio-labeled neurotransmitter analogs, have the specificity and affinity for the uptake-1 mechanism.\textsuperscript{7} In this study, we found a significantly lower baseline delayed H/M ratio and a higher baseline H/M washout rate in patients with HF than in control subjects, consistent with previous studies that showed downregulation of the uptake-1 carrier protein at the synaptic level.\textsuperscript{22-24}

**Rebalancing Cardiac Autonomic Function by CRT**

Consistent with the CRT outcomes from multicenter randomized trials\textsuperscript{1-3, 25} our study findings also support the benefits of CRT with regard to improving NYHA functional class, the distance of the 6-minute walk, LV systolic function, and reversal of LV structural remodeling. These significant improvements in HF were revealed at 3 months, and sustained at 6 months after CRT. These symptomatic and hemodynamic benefits continued to be seen at a mean follow-up duration of 3 years. We showed that at the sympathetic terminal level, CRT upregulates presynaptic 123I-MIBG uptake and retention, as evidenced by increased H/M ratio and reduced H/M washout rate, and confirmed findings of previous reports (of small patient groups).\textsuperscript{18, 26, 27} Further, we showed that these effects were mainly observed in patients who responded to CRT by a reduction of LVESV index. In parallel, heart rate variability, as measured by SDNN and SDANN, were improved by CRT, indicating a favorable rebalance of cardiac sympathetic...
function and vagal cardiac reflex response. Our study results, therefore, uniquely suggest that CRT, as an additional and effective therapy for HF, improves cardiac sympathetic activity beyond that achieved by pharmacologic therapy with β-blockers or renin-angiotensin-aldosterone axis inhibition.

**Cardiac Sympathetic Reserve and CRT Response**

Echocardiographically determined dyssynchrony indices inconsistently identify those who would respond to CRT. Single-center studies have shown that traditional echocardiographic techniques, including tissue Doppler imaging, have the ability to distinguish CRT responders from nonresponders.\(^{16, 28-30}\) However, the PROSPECT (Predictors of Response to CRT) multicenter trial showed that the ability of echocardiographic parameters to predict clinical composite score response varied widely.\(^{15}\) In our study, we found that CRT responders had longer 6-min walk distance at baseline, representing their greater exercise tolerance. The physical functional status was related to the improvement in LV function as observed from this study. The less-impaired presynaptic uptake function was associated with a greater LV reverse remodeling as judged by the 15% reduction in the LVESV index. Cardiac damage is followed by nerve sprouting, and nerve sprouts that successfully connect with viable myocardium will survive, whereas those located in irreversibly damaged areas such as within the future scars regress during the post-infarct period.\(^{31}\) We speculate that \(^{123}\)I-MIBG imaging detects not only sympathetic nerve activity but also indirectly suggest a successful connection of these nerves within viable myocardial tissue.

**Limitations**

The study sample size was less robust to evaluate the predictive value of measurements. A larger-scale \(^{123}\)I-MIBG imaging study will be beneficial to assess the predictive value of CRT response in clinical applications. Medications used by patients in the study may affect assessment of cardiac autonomic function. However, all patients were maintained on a stable
dosage of medications during the study. β-Blocker use may affect interpretation of $^{123}$I-MIBG studies. However, withdrawal from β-blocker therapy is not ethical; hence, to minimize the effect of variations in medications, the same type of β-blocker and stable dosage were maintained carefully throughout the study. Using a single criterion of LVESV index change to assess CRT response may have the limitation to evaluate response to CRT; however, at present time a consensus on the criteria in assessing CRT response is lacking, based on a recent meta-analysis evaluating response to CRT by Fornwalt et al.²⁵

**Conclusion**

To our knowledge, this is the first study to comprehensively investigate the impact of CRT on cardiac autonomic function, specifically, neuronal receptor function. Cardiac sympathetic reserve may be considered a characteristic of the candidate who potentially will benefit from CRT. For patients who may have insufficient myocardial adrenergic preservation, consideration of therapeutic options other than CRT may be reasonable. Larger studies are needed to confirm these findings.

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References


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<table>
<thead>
<tr>
<th>Characteristics</th>
<th>CRT (n=45)</th>
<th>Control (n=20)</th>
<th>p value</th>
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<tr>
<td>Age, mean (SD), y</td>
<td>67.8 (8.8)</td>
<td>67.3 (5.8)</td>
<td>0.57</td>
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<td>Men, No. (%)</td>
<td>37 (82.2)</td>
<td>10 (50.0)</td>
<td>0.007</td>
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<td>Body mass index, mean (SD). kg/m²</td>
<td>29.8 (4.7)</td>
<td>29.2 (5.3)</td>
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<td>29 (64.4)</td>
<td>0 (0)</td>
<td>&lt;0.001</td>
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<td>Myocardial infarction, No. (%)</td>
<td>22 (48.9)</td>
<td>0 (0)</td>
<td>0.001</td>
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<td>18 (40.0)</td>
<td>0 (0)</td>
<td>&lt;0.001</td>
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<td>Hypertension, No. (%)</td>
<td>23 (51.1)</td>
<td>9 (45.0)</td>
<td>0.65</td>
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<td>Diabetes mellitus, No. (%)</td>
<td>19 (42.2)</td>
<td>2 (10.0)</td>
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<td>New York Heart Association class, Median (Q1, Q3)</td>
<td>3.0 (3.0, 3.0)</td>
<td>1.0 (1.0, 1.0)</td>
<td>&lt;0.001 *</td>
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<td>III</td>
<td>40 (88.9)</td>
<td>0 (0)</td>
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<td>IV</td>
<td>5 (11.1)</td>
<td>0 (0)</td>
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<td>Ischemic cardiomyopathy, No. (%)</td>
<td>26 (57.8)</td>
<td>0 (0)</td>
<td>&lt;0.001</td>
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<td>Medical therapy, No. (%)</td>
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<td>Aspirin</td>
<td>34 (75.5)</td>
<td>1 (5.0)</td>
<td>&lt;0.001</td>
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<td>β-Blocker</td>
<td>41 (91.1)</td>
<td>2 (10.0)</td>
<td>&lt;0.001</td>
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<td>Statin</td>
<td>28 (62.2)</td>
<td>3 (15.0)</td>
<td>&lt;0.001</td>
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<td>39 (86.7)</td>
<td>1 (5.0)</td>
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<td>Digoxin</td>
<td>27 (60.0)</td>
<td>0 (0)</td>
<td>&lt;0.001</td>
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<td>Distance of 6-minute walk, mean (SD), m</td>
<td>351 (108)</td>
<td>464 (79)</td>
<td>&lt;0.001</td>
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<td>LV ejection fraction, mean (SD), %</td>
<td>25.6 (5.2)</td>
<td>61.3 (4.3)</td>
<td>&lt;0.001</td>
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<td>LV end-diastolic volume index, mean (SD), mL/m²</td>
<td>100.0 (33.9)</td>
<td>43.5 (7.4)</td>
<td>&lt;0.001 *</td>
</tr>
<tr>
<td>LV end-systolic volume index, mean (SD), mL/m²</td>
<td>76.8 (26.3)</td>
<td>16.8 (3.5)</td>
<td>&lt;0.001 *</td>
</tr>
</tbody>
</table>
### Pulmonary artery systolic pressure, mean (SD), mm Hg

- 47.3 (16.9)
- 28.9 (4.4)
- <0.001 *

### Interventricular conduction delay, mean (SD), milliseconds

- 37.6 (22.6)
- 17.0 (15.0)
- <0.001 *

### SD of differences in LV 12 segment by tissue Doppler, mean (SD), milliseconds

- 42.8 (19.2)
- 44.1 (21.9)
- 0.55

### SD of differences in LV 12 segment by strain, mean (SD), milliseconds

- 105.6 (43.9)
- 47.5 (11.2)
- <0.001

### Plasma nerve growth factor, mean (SD), ng/dL

- 15.4 (15.3)
- 10.7 (6.0)
- 0.58 *

### SDNN, mean (SD), ms

- 87.2 (34.5)
- 111.2 (34.0)
- 0.008

### SDANN, mean (SD), ms

- 83.8 (30.0)
- 104.1 (26.9)
- 0.005 *

### Initial H/M ratio, mean (SD)

- 2.01 (0.57)
- 2.56 (0.25)
- 0.001 *

### Delayed H/M ratio, mean (SD)

- 1.77 (0.58)
- 2.55 (0.44)
- <0.001 *

### H/M washout rate, mean (SD), %

- 50 (20)
- 25 (12)
- 0.001

**Abbreviations:** H/M, heart/mediastinum; LV, left ventricular; SD, standard deviation; SDANN, standard deviation of the average normal-to-normal intervals in all 5-minute segments; SDNN, standard deviation of all normal-to-normal intervals.

* - rank-sum test
Table 2. Effect of Cardiac Resynchronization Therapy

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Baseline</th>
<th>3 Months After CRT</th>
<th>6 Months After CRT</th>
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<tr>
<td>New York Heart Association class, mean (SD) Median (Q1, Q3)</td>
<td>3.0 (3.0, 3.0)</td>
<td>2.0 (2.0, 3.0)++</td>
<td>2.0 (2.0, 3.0)++</td>
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<td>Distance of 6-minute walk, mean (SD), m</td>
<td>352 (112)</td>
<td>409 (105)**</td>
<td>429 (113)**</td>
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<tr>
<td>LV ejection fraction, mean (SD), %</td>
<td>25.8 (5.3)</td>
<td>30.7 (7.8)**</td>
<td>33.4 (9.4)**</td>
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<td>LV end-diastolic volume index, mean (SD), mL/m²</td>
<td>98.5 (31.4)</td>
<td>91.1 (26.2)**</td>
<td>88.9 (26.1)**</td>
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<tr>
<td>LV end-systolic volume index, mean (SD), mL/m²</td>
<td>75.8 (24.2)</td>
<td>63.9 (22.2)**</td>
<td>60.3 (24.1)**</td>
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<td>Mitral regurgitation grade, mean (SD)</td>
<td>1.76 (1.27)</td>
<td>2.21 (0.90)**</td>
<td>1.21 (0.95)**</td>
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<td>Left atrial volume index, mean (SD), mL/m²</td>
<td>52.7 (15.8)</td>
<td>48.7 (15.0)*</td>
<td>48.2 (13.9)*</td>
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<td>Pulmonary artery systolic pressure, mean (SD), mm Hg</td>
<td>45.4 (15.5)</td>
<td>41.4 (16.0)</td>
<td>38.7 (13.2)*</td>
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<td>Interventricular conduction delay, mean (SD), milliseconds</td>
<td>37.6 (22.6)</td>
<td>26.1 (18.0)*</td>
<td>27.7 (15.0)*</td>
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<tr>
<td>SD of differences in LV 12 segment by strain, mean (SD), ms</td>
<td>106.4 (43.3)</td>
<td>88.2 (34.8)*</td>
<td>84.7 (26.1)**</td>
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<td>Plasma nerve growth factor, mean (SD), ng/ml</td>
<td>16.3 (16.2)</td>
<td>12.6 (18.2)</td>
<td>15.9 (20.5)</td>
</tr>
<tr>
<td>SDNN, mean (SD), milliseconds</td>
<td>85.6 (31.6)</td>
<td>109.9 (31.1)++</td>
<td>114.8 (39.0)**</td>
</tr>
<tr>
<td>SDANN, mean (SD), milliseconds</td>
<td>82.62 (23.0)</td>
<td>92.5 (28.0)</td>
<td>100.5 (34.8)**</td>
</tr>
<tr>
<td>Delayed H/M ratio, mean (SD)</td>
<td>1.82 (0.58)</td>
<td>--</td>
<td>1.97 (0.59)*</td>
</tr>
<tr>
<td>H/M washout rate, mean (SD), %</td>
<td>48 (19)</td>
<td>--</td>
<td>37 (22)*</td>
</tr>
</tbody>
</table>

Abbreviations: H/M, heart/mediastinum; LV, left ventricular; SD, standard deviation; SDANN, standard deviation of the average normal-to-normal intervals in all 5-minute segments; SDNN, standard deviation of all normal-to-normal intervals. * p<0.05 as compared to baseline (t-test), **p<0.01 as compared to baseline (t-test). + p < 0.05 as compared to baseline (signed-rank test). ++ p < 0.01 as compared to baseline (signed-rank test).
**Figure Legends**

**Figure 1.** Differences Between Responders and Nonresponders Before CRT. A, Graphs show baseline values for left ventricular ejection fraction (LVEF), left ventricular end-systolic volume (LVESV) index, interventricular conduction delay, and intraventricular conduction delay (Mean ± SD). B, Graphs show baseline values for delayed heart/mediastinum (H/M) ratio, and metaiodobenzylguanidine iodine 123 H/M washout rate (Mean ± SD).

**Figure 2.** Correlation Between Change in Left Ventricular End-Systolic Volume (LVESV) Index After CRT and Baseline Values. A, iodine 123 delayed heart/mediastinum (H/M) ratio. B, Metaiodobenzylguanidine H/M washout rate.
Cardiac Sympathetic Reserve and Response to Cardiac Resynchronization Therapy
Yong-Mei Cha, Panithaya Chareonthaitawee, Ying-Xue Dong, Bradley J. Kemp, Jae K. Oh, Chinami Miyazaki, David L. Hayes, Robert F. Rea, Samuel J. Asirvatham, Tracy L. Webster, Connie M. Dalzell, David O. Hodge, Regina M. Herges, Yan-zhong Yong, Yanhua Zhang and Peng-Sheng Chen

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Supplemental Material

Cardiac Sympathetic Reserve and Response to Cardiac Resynchronization Therapy

Yong-Mei Cha, MD, et al.
Abbreviations

EDTA, ethylenediaminetetraacetic acid

LV, left ventricle, left ventricular

$^{123}$I-MIBG, iodine 123 metaiodobenzylguanidine
Online Supplement to the Methods

Echocardiography
Echocardiographic studies were performed and interpreted by a cardiologist who was masked to the patients’ clinical status. All echocardiographic parameters were measured in triplicate and averaged. Echocardiographic parameters included left ventricular (LV) ejection fraction (derived from 2-dimensional measurements of diastolic and systolic LV dimension or volumetric analysis using the method of disks), pulmonary artery systolic pressure (estimated from the tricuspid regurgitant velocity and an estimate of right atrial pressure), mitral regurgitation severity grade (0=none/trivial; 1=mild; 2=moderate; 3=severe), and LV end-diastolic volume and LV end-systolic volume (calculated by using the biplane method). Tissue Doppler and strain imaging were used to assess LV dyssynchrony. Intraventricular dyssynchrony was determined by the standard deviation of timing intervals from QRS onset to peak negative strain from 12 basal and mid LV segments. The interventricular mechanical delay was defined as the timing difference between pulmonary valve and aortic valve opening, as measured by pulsed-wave Doppler echocardiography.

24-Hour Ambulatory Electrocardiographic Monitoring
The stored data from 24-hour ambulatory electrocardiographic recordings (Del Mar Avionics, Irvine, California) were analyzed by an independent observer who was masked to the patients’ clinical status. Time domain analysis of heart rate variability included the standard deviation of all normal-to-normal R-R intervals and the standard deviation of the average normal-to-normal R-R intervals in all 5-minute segments.¹

Plasma Biomarker Measurements
Plasma nerve growth factor concentrations were detected with sandwich enzyme-linked immunosorbent assay. All assays were performed on F-bottom 96-well plates (Nunc, Wiesbaden, Germany). Tertiary antibodies were conjugated to horseradish peroxidase. Nerve growth factor content was quantified against a standard curve calibrated with known amounts of protein. All samples were assayed in triplicate and expressed as means.²

Metaiodobenzylguanidine Iodine 123 Scintigraphy

All metaiodobenzylguanidine iodine 123 (¹²³I-MIBG) imaging studies were performed at rest after an overnight fast. Thyroid uptake was blocked by potassium iodide (200 mg), administered orally 1 hour before intravenous injection of ¹²³I-MIBG (10 mCi). ¹²³I-MIBG scintigraphy was performed with a standard dual-head gamma camera (Hawkeye, GE Medical Systems, Haifa, Israel) with medium-energy collimators. Fifteen minutes (initial) and 240 minutes (delayed) after the injection of the radiopharmaceutical, planar images of the thorax were acquired for 10 minutes in the anterior position. A 20×20-pixel region of interest was placed over the upper mediastinum. The heart/mediastinum ratio was calculated as mean counts per pixel over the left ventricle divided by mean counts per pixel in the upper mediastinum. The decay-corrected myocardial ¹²³I-MIBG washout was calculated according to the following algorithm.³:

\[
\text{Cardiac } ¹²³\text{I-MIBG washout} = \frac{(\text{early heart count density} - \text{late heart count density})}{(\text{early heart count density})} \times 100\%
\]

No patients were taking sympathomimetic agents or other medications known to interfere with MIBG uptake at the time of ¹²³I-MIBG imaging. The techniques of imaging were kept the same for individuals at baseline and 6 months.
References