Mechanisms of respiratory sinus arrhythmia in patients with mild heart failure

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Received 8 June 2000; accepted in final form 10 August 2000

SPECTRAL ANALYSIS of heart rate (HR) variability (HRV) is a widely accepted method for evaluating the cardiac autonomic modulation in physiological and pathological conditions (27). In particular, it is well established that in the supine position and at a breathing frequency >0.15 Hz the high-frequency (HF) component of the HRV power spectrum (i.e., respiratory sinus arrhythmia) provides a measure of “cardiac parasympathetic responsiveness,” since it reflects the modulation of vagal cardiac efferent activity by breathing and the sinoatrial response to that modulation (23, 24). However, a small HF component has been seen in the transplanted denervated human heart (2, 3, 18, 25) and in healthy subjects after autonomic blockade (7, 23), suggesting that breathing-related changes in atrial transmural pressure (6, 21) or in the direction of the cardiac axis (17) may be responsible for at least part of the HRV in the HF range. In young healthy subjects, the contribution of nonneural mechanisms to the HF power of the HRV increases from 1% at rest to 30% during exercise (7). This implies that, in the presence of vagal withdrawal, the HF component may significantly overestimate cardiac parasympathetic responsiveness, especially when its power is normalized for the R-R interval (RR) variance (16). These findings may be applicable to patients with chronic heart failure (CHF) who are known to have impaired cardiac parasympathetic responsiveness and a reduced HRV (5, 9, 22). Experimental data, however, indicate that right atrial stretch may suppress neural and nonneural components of respiratory sinus arrhythmia (14), suggesting that the relative contribution to the HF power in patients with CHF may remain small, despite a reduction in HRV. To test this hypothesis, we calculated the relative contribution of autonomic and nonneural inputs to the HF power of the HRV in patients with mild CHF and in healthy age-matched controls.

METHODS

Twenty patients with stable heart failure [New York Heart Association (NYHA) Class II, mean age 61 ± 2 yr] and 11 age-matched healthy subjects (mean age 58 ± 2 yr) volunteered for the study. The latter were in good health as indicated by medical history, physical examination, electrocardiogram (ECG), and arterial blood pressure (BP) measurements. None of healthy subjects was taking any medication. All patients had been in stable CHF for >3 mo. Fifteen patients had had a documented myocardial infarction, one had chronic ischemic heart disease, and four had dilated cardiomyopathy. All patients were on angiotensin-converting enzyme inhibitors and furosemide, and one was on a β-blocker. None was on digitalis or antiarrhythmic drugs. The average radionuclide left ventricular ejection fraction was 25 ± 6% (mean ± SD).

Subjects with a history of atopic allergy, glaucoma, diabetes mellitus, atrial fibrillation, angina pectoris, or ECG evidence of ischemia-limiting exercise, chronic obstructive pulmonary disease, and liver or renal failure were excluded.

Written consent was obtained after the subjects were informed of the procedures and risks involved in the study. The protocol was approved by the Central Oxford Research Ethics Committee.

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Baseline spontaneous breathing and for 10 min during controlled breathing was then tested (26). Briefly, three to five rapid intravenous injections of phenylephrine hydrochloride (Boots Pharmaceuticals) were given at ~3-min intervals. The initial dose of 0.05 mg was adjusted to obtain an increase in systolic BP between 10 and 20 mmHg. Beat-by-beat BP recordings from the finger were obtained noninvasively by an infrared photoplethysmograph (Finapres 2300 BP monitor, Ohmeda) while the RR was measured from the ECG. The reflex lengthening of the RR in response to the phenylephrine-induced increase in systolic BP [i.e., the "baroreflex sensitivity," in ms/mmHg (26)] was taken as an index of reflex vagal activity.

A 0.1% NaCl solution of the ganglion blocker trimethaphan camsylate (Arfonad, Roche) was then infused through an indwelling cannula in an antebrual vein. Beat-by-beat BP and ECG were monitored continuously during the infusion. The initial infusion rate of 3 mg/min was slowly increased until the RR response to phenylephrine was abolished. During ganglion blockade (GB), the dose of phenylephrine was adjusted to achieve a peak systolic BP similar to that obtained at baseline. The use of GB to inhibit the neural inputs to the heart was preferred to the more conventional β-adrenergic and muscarinic receptor antagonism for two reasons: 1) Unlike propranolol or atropine, trimethaphan camsylate has a very short half-life. This meant that we could reverse possible adverse reactions very rapidly and shorten considerably the period of observation after the experiment. 2) In our hands, high doses of atropine (i.e., 0.04 mg/kg) do not block the cardiac baroreceptor reflex in all subjects.

When GB was reached, recordings of ECG, breathing frequency, and V_t during spontaneous and controlled breathing were repeated.

Power spectral analysis of HRV. The ECG and breathing traces were digitized on-line by a 12-bit analog-to-digital converter (AT-Codas, Dataq Instruments) at a sampling rate of 600 Hz. The QRS complex was detected by identifying the points of the low-pass-filtered first derivative of the ECG signal, which exceeded an adaptive threshold. Each QRS complex and its triggering were verified by visual inspection. The breathing signal was sampled once every cardiac cycle. Time series of 256 consecutive RRs were used for spectral analysis. The autoregressive method, which was used to evaluate the power spectral density of the RR series, has been described in detail previously (7). Briefly, a computer program first calculated the autoregressive coefficients using the Levinson-Durbin algorithm, and the model order was chosen by the Akaike information criterion starting from a

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**Table 1. HRV before and during GB in patients with mild heart failure and age-matched controls**

<table>
<thead>
<tr>
<th></th>
<th>RR, ms</th>
<th>SDRR, ms</th>
<th>LE, ms</th>
<th>HE, ms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
<td>CHF</td>
<td>Controls</td>
<td>CHF</td>
<td>Controls</td>
</tr>
<tr>
<td></td>
<td>745.5 ± 49.3</td>
<td>867.9 ± 50.4</td>
<td>25.63 ± 4.03</td>
<td>35.53 ± 2.82‡</td>
</tr>
<tr>
<td>GB</td>
<td>635.1 ± 37.3*</td>
<td>648.0 ± 48.0°</td>
<td>6.55 ± 0.47*</td>
<td>5.80 ± 0.48*</td>
</tr>
</tbody>
</table>

**Controlled breathing at 0.16 Hz**

<table>
<thead>
<tr>
<th></th>
<th>CHF</th>
<th>Controls</th>
<th>CHF</th>
<th>Controls</th>
<th>CHF</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>745.0 ± 51.0</td>
<td>866.3 ± 51.0</td>
<td>27.91 ± 4.12</td>
<td>45.66 ± 4.61‡</td>
<td>11.57 ± 2.59</td>
<td>12.56 ± 1.42‡</td>
</tr>
<tr>
<td>GB</td>
<td>643.0 ± 37.1°</td>
<td>636.6 ± 51.5*</td>
<td>7.07 ± 0.73°</td>
<td>6.24 ± 0.70*</td>
<td>0*</td>
<td>0*</td>
</tr>
</tbody>
</table>

Values are means ± SE of 15 patients with chronic heart failure (CHF) and 9 controls. HRV, heart rate variability; GB, ganglion blockade; RR, R-R interval; SDRR, RR standard deviation; LF, amplitude of the low-frequency component; HF, amplitude of the high-frequency component. *P < 0.005, GB vs. baseline; †P < 0.05, controlled breathing vs. spontaneous breathing; ‡P < 0.05, CHF vs. controls.
minimum order of 12. A spectral decomposition method was then applied to evaluate the power and the central frequency of the low-frequency (LF, 0.04–0.15 Hz) and high-frequency (HF, 0.15–0.50 Hz) components. The relative contribution of nonneural mechanisms to the HF power was calculated as follows

\[
\frac{\text{HF power after GB (ms}^2\text{)}}{\text{HF power before GB (ms}^2\text{)}} \times 100
\]

The very-low-frequency component (<0.04 Hz) was examined to assess the presence of narrow peaks indicating periodic breathing (19).

Cross-spectral analysis. To assess the relationship between respiration and HF oscillations, the cross spectrum and squared coherence function of the HRV and the breathing signal were calculated as described by Pagani et al. (20). Briefly, cross spectra were computed by fast Fourier transformation, using a triangular window, on successive 50% overlapping series of 64 RRs each. The squared coherence function was used to evaluate the correlation between breathing and RR oscillations at the same frequency. The value of this function is regarded as an analog of the squared correlation coefficient (\(r^2\)) and ranges from 0 to 1.

Statistical analysis. Values are means ± SE. ANOVA (SuperANOVA, Abacus Concepts) was used to compare the data within the protocol stages and between patients with CHF and healthy subjects. To achieve a normal distribution and to normalize the variance of the data between stages, comparisons were made using the square root of the power of the spectral components (i.e., their amplitude, in ms). Nonparametric statistic was employed to compare the contribution of nonneural mechanisms to the HF power in CHF patients and controls. For this variable, data are given as geometric means. Statistical significance was accepted at \(P < 0.05\).

RESULTS

Two CHF patients and one control subject could not complete the study, since they developed a vasovagal reaction (bradycardia, nausea, sweating, and hypotension) shortly after the start of the infusion of trimethaphan camsylate. In two CHF patients and one control subject, the infusion of trimethaphan camsylate was not attempted, since the presence of frequent ectopic beats did not permit a satisfactory analysis of the baseline ECG recordings.

GB was usually obtained with an infusion rate of trimethaphan camsylate between 5 and 6 mg/min. At these doses, the increase in BP induced by the intra-
venous injection of phenylephrine was associated with a modest shortening of the RR in four subjects (Fig. 1) and no change in the others, with the exception of one CHF patient, in whom a trimethaphan camsylate infusion of 6 mg/min did not completely abolish the RR lengthening associated with phenylephrine. Since high doses of trimethaphan camsylate can cause respiratory depression, it was considered unsafe to increase the rate of infusion further, and the data from this patient were not included in the final analysis. During GB, all subjects experienced dry mouth and cycloplegia.

Baseline measurements. The mean RR did not differ between CHF patients \( (n = 15) \) and age-matched control subjects \( (n = 9) \); however, the standard deviation of the RR was lower in CHF patients during spontaneous \( (P < 0.05) \) and controlled \( (P < 0.001) \) breathing (Table 1). Likewise, patients had lower baroreflex sensitivity \( (4.34 \pm 0.81 \text{ vs. } 10.85 \pm 2.31 \text{ ms/mmHg, } P < 0.05) \) and a reduced HF component (Table 1). There were no significant differences in \( V_I, V_T \) (Table 2), or spontaneous breathing frequency between control subjects and CHF patients \( (0.24 \pm 0.02 \text{ and } 0.28 \pm 0.03 \text{ Hz, respectively}) \). Controlled breathing at 0.16 Hz increased \( V_T \) (Table 2) and the amplitude of the HF component (Table 1) in both groups.

The amplitude of LF oscillations was significantly greater in healthy controls than in CHF patients during spontaneous breathing; this difference, however, was no longer present during controlled breathing (Table 1). The center frequency of the LF component did not differ between the two groups \( (0.09 \pm 0.01 \text{ vs. } 0.10 \pm 0.01 \text{ Hz during spontaneous breathing and } 0.09 \pm 0.01 \text{ vs. } 0.09 \pm 0.01 \text{ Hz during controlled breathing}) \).

During spontaneous breathing, narrow peaks in the very-low-frequency range (centered at \( -0.02 \text{ Hz} \)) of the HRV power spectrum were found in two CHF patients. Analysis of the respiration signal showed that they were due to periodic breathing. This abnormal breathing pattern was not seen during controlled breathing or GB (data not shown).

GB. GB caused a significant reduction in the mean RR and its standard deviation (Table 1) in both groups. The RR fluctuations in the LF range were completely abolished by GB, but some degree of respiratory sinus arrhythmia persisted in all subjects and did not differ in magnitude between CHF patients and healthy controls (Table 1, Figs. 2 and 3). The correlation between RR fluctuations in the HF range and the breathing signal was not affected by GB (coherence values of \( 0.82 \pm 0.03 \text{ and } 0.89 \pm 0.02 \text{, respectively}) \), indicating that a close relationship between these signals persisted after neural control of sinoatrial node activity was abolished.

There was no significant change in \( V_I \) or \( V_T \) in either group with GB (Table 2). Breathing frequency was not affected by GB and did not differ between controls and CHF patients \( (0.24 \pm 0.03 \text{ and } 0.27 \pm 0.02 \text{ Hz, respectively}) \). Controlled breathing significantly increased \( V_T \) (Table 2) but did not affect the amplitude of the HF component after GB (Table 1).

Fig. 3. Tachogram (top) and power spectra of the heart rate variability (HRV, middle) and breathing signal (bottom) before and during GB in a chronic heart failure (CHF) patient. Note the reduction in amplitude of HF oscillations before GB compared with Fig. 2. As in Fig. 2, nonneural HF oscillations are responsible for most of the residual HRV during GB, whereas LF oscillations are completely abolished.
Nonneural contribution to the HF power in CHF patients and in healthy controls. During spontaneous breathing, the relative contribution of nonneural mechanisms to the HF power was 3% in healthy controls (range 0.7–30%) and 15% in patients with CHF (range 1–76%, \( P < 0.005 \) vs. controls). During controlled breathing, nonneural mechanisms accounted for 1% of the HF power in healthy controls (range 0.2–13%) and 5% in CHF patients (range 1–44%, \( P < 0.005 \) vs. controls and \( P < 0.01 \) for the effect of controlled breathing at 0.16 Hz in both groups; Fig. 4).

In all subjects, the natural logarithm of the nonneural contribution to HF was inversely related to the RR standard deviation (Fig. 5; adjusted \( r^2 = 0.53 \) during spontaneous breathing and 0.50 during controlled breathing, \( P < 0.0001 \) for both).

**DISCUSSION**

Heart failure is associated with neurohumoral activation and a reduction in cardiac vagal responsiveness (10). Spectral analysis of the HRV in these patients has shown that the absolute power in the LF range decreases with the worsening of the disease and is often absent in NYHA Class IV patients (18). Likewise, the absolute power of the HF component has been found to be significantly decreased from the early stages of the disease (8, 11). However, HR fluctuations in the HF range are present even in the most advanced stages of CHF, where they can account for most of the short-term HRV (11, 18). To explain this finding, it has been suggested that respiratory sinus arrhythmia in severe CHF might be entirely mediated by nonneural mechanisms (11, 18). Experiments in anesthetized pigs, however, have shown a reduction in neural and nonneural HR oscillations in the HF range with atrial stretch (14), suggesting that nonneural modulation of HR may also be suppressed in patients with CHF.

The present study shows that small HR fluctuations synchronous with breathing persist after GB, and their magnitude is similar in healthy subjects and in patients with mild CHF. These residual HF fluctuations are unlikely to be vagally mediated, since, in the dose range employed in this study, trimethaphan camsylate completely abolished the reflex bradycardia in response to the phenylephrine-induced increase in BP (Fig. 1). Moreover, the LF component was abolished by GB in all subjects (Table 1). Since sympathetic and vagal activities have been shown to contribute to the HRV in this frequency range (23), its disappearance with high doses of trimethaphan camsylate provides further evidence for the adequacy of GB. We also show that, during spontaneous breathing, nonneural mechanisms contribute significantly (i.e., 15%) to the HF power in patients with mild CHF but not in healthy age-matched controls (3%). Since nonneural modulation of HR was preserved in CHF patients, its contribution to the HF component was inversely related to HRV (as assessed by the RR standard deviation, Fig. 5). Taken together, our results indicate that the HF power of the HRV can overestimate cardiac parasympathetic responsiveness in patients with mild CHF and, indeed, whenever the HRV is significantly reduced. This is especially the case when HF is expressed in “normalized” units (i.e., as a percentage of the RR variance) or as LF-to-HF ratio (1). Our findings would have been more dramatic if we had included patients with severe CHF. Indeed, we found that the contribution of nonneural oscillation to the HF component of the HRV was ~50% in four NYHA Class III patients.
acted by the reduction in breathing frequency and $\dot{V}_I$, breathing frequencies that gave the same $\dot{V}_I$ also resulted in similar nonneural HF power (21). Consistent with these findings, controlled breathing at 0.16 Hz did not affect the amplitude of the HF component after GB (Table 1), since the increase in $\dot{V}_t$ was counteracted by the reduction in breathing frequency and $\dot{V}_t$ did not change compared with spontaneous breathing (Table 2).

Summary. This study shows that the relative contribution of nonneural mechanisms to the respiratory sinus arrhythmia is significantly increased in patients with mild CHF, accounting on average for 15% (range 1–77%) of the HF component of the HRV (vs. 3% in controls). These findings suggest that spectral analysis of HRV should be interpreted with caution in all patients with CHF (not just in those with terminal disease) or, indeed, whenever the HRV is significantly reduced [e.g., during exercise (7)]. Since RR oscillations in the LF range appear to be entirely neurally mediated whereas those in the HF range are clearly not, the use of normalized units or of the LF-to-HF ratio in CHF patients would lead to a significant overestimation of the level of cardiac vagal responsiveness. However, the accuracy of respiratory sinus arrhythmia as a vagal index can be improved by controlled breathing, since this maneuver appears to increase the vagal contribution to respiratory sinus arrhythmia without affecting its nonneural component.

We gratefully acknowledge the support of the Garfield Weston Trust and the Norman Collisson Foundation.

REFERENCES


