Cardiac Responses during Uninterrupted Treadmill Exercise and Recovery

Measurement by Systolic Time Intervals

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In 12 normal subjects, use of ear densitography permitted measurement of systolic time intervals (STI) during uninterrupted treadmill exercise to over 90 percent maximal heart rate on a modified Bruce protocol. Results for control (sitting → standing) → end-exercise at 18 minutes → 10 minutes' sitting recovery were—heart rate (HR): (77→86) → 171→98 beats per minute; pre-ejection period (PEP): (106→111) → 49→110 msec; ejection time index (ETI) (351→330) → 380→366 msec; PEP/LVET (0.42→0.49) → 0.29→0.45. Heart rate increased steadily to 18 minutes. In contrast, the PEP/LVET decrease was almost complete by three minutes and both ETI and PEP responses were bimodal with respective plateaus between three and six minutes and three and nine minutes. All STI and HR curves showed rapid restitution during early recovery. The changes during treadmill exercise were numerically comparable to those during bicycle exercise at a common heart rate. The results indicate that it is technically feasible to measure systolic time intervals with precision during uninterrupted treadmill exercise; responses to treadmill exercise were in the direction expected and quantitatively comparable to bicycle exercise at comparable stress level. These observations provide the technical and physiologic bases for applying this method in clinical treadmill exercise testing.

The usefulness of systolic time intervals (STI) as indicators of physiologic and pathologic responses to cardiocirculatory challenges is well established.1–3 Until recently, exercise test responses utilizing this convenient noninvasive method had to be recorded either during interrupted exercise or after the conclusion of exercise.4–6 The methodology for STI responses during uninterrupted bicycle exercise has been developed and the results reported in some detail.7–11 Development of the ear densitograph simplified constant recording during exercise, removed problems of pulse wave artifacts and permitted elimination (after baseline control traces) of the phonocardiogram.9,12,18

For accurate exercise results, it is extremely important to avoid any interruption during stress testing, owing to the striking immediate changes following cessation of exercise which have been noted in continuous recordings.11 Utilizing the ear densitograph,11 we studied the exercise and recovery responses of systolic time intervals in subjects who achieved over 90 percent maximal heart rate in completing 18 minutes of a modified Bruce protocol.

MATERIAL AND METHODS

Subjects

The subjects were 12 healthy normally active male volunteers aged 25 to 50 years (mean ± SD = 35 ± 8 years). None was a trained athlete or was on medication. Criteria for inclusion consisted of a normal medical history, physical examination, 12-lead ECG and chest film.

Recordings

Subjects were studied uniformly in the laboratory in mid-morning in the postabsorptive state. Data for systolic time intervals (STI) were recorded from the ear densitograph pulse derivative,11 and electrocardiogram preceded by baseline “triple trace” (ECG-phonocardiogram-pulse wave) to obtain pulse transmission time12 on a Hewlett-Packard No. 508-100A recorder according to methods previously described.11,12 The only addition to previous techniques for STI was that leads I, aVF, and V5 were also recorded simultaneously to exclude any individuals who might develop ST segment deviations.

Protocol

Subjects sat for two minutes (2'), then stood for 2', then exercised on a Collins treadmill according to a modified...
Bruce protocol: six 3' stages without interruption at speeds of 1.7, 1.7, 2.5, 3.4, 4.2 and 5.0 miles per hour (mph) and corresponding elevations of 5, 10, 12, 14, 16 and 18 percent (%). This was followed by a 10' recovery period with subjects sitting.

**Measurements and Calculations**

Heart rate (HR), pre-ejection period (PEP), left ventricular ejection time (LVET), ejection time index (ETI) and PEP/LVET were measured as previously described.\(^7\)\(^{-13}\) STI were calculated from means of five consecutive beats for each of the following points of measurement: last beats of sitting control at 2'; last beats of 2' standing control period; last beats (end of 3') of each stage of the six-stage modified Bruce protocol; immediate five post-exercise beats while still standing; and post-exercise (sitting) at 2', 5' and 10'.

**Statistical Analysis**

Pre-exercise standing control values were compared with exercise and immediate post-exercise beats. Sitting control values were compared with 2', 5' and 10' of recovery. The t-test for paired samples was used at each point to compare with control values (PΔc). Percentage changes from control (PΔc%) were calculated. Where necessary (see discussion) the t-test was applied to particular points and adjacent values. Standard deviations (SD) and errors (SE) were calculated.

**RESULTS**

Results for the time course of exercise and recovery STI and corresponding statistical data are summarized in Figure 1 and Tables 1 to 5.

**ECG Responses**

No subject developed ST segment deviations, typical of a normal group.

**Postural Changes During Control Period**

Postural changes, noted only for completeness (they were not part of the study), were typical of those reported for normal subjects.\(^14\)\(^{-15}\) Thus, from sitting to standing, heart rate, pre-ejection period and PEP/LVET rose, and LVET and ETI fell.

**Heart Rate Responses**

Heart rate increased gradually and steadily throughout the test to the 18' end point (171

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**FIGURE 1.** Time-course of changes in systolic time intervals during uninterrupted treadmill exercise and recovery. Legend and units for individual curves at upper right. Bars = standard errors. **Abbreviations:** ETI—ejection time index; PEP—pre-ejection period; LVET—left ventricular ejection time; HR—heart rate; msec—milliseconds; mph—miles per hour; C—control; (') minutes; R—recovery. R\(_i\) denotes immediate recovery, i.e., first five beats after 18' end-exercise measurement with subjects still standing. Stippled zones indicate subjects sitting (left—sitting control; right—sitting recovery). NB—postural changes during sitting and standing control; steady HR rise during exercise; plateaus during exercise for ETI (3' to 9') and PEP (3' and 6'); rapid fall of PEP/LVET almost to a "floor" value.
Table 1—Responses During Treadmill Exercise and Recovery

<table>
<thead>
<tr>
<th>Heart Rate</th>
<th>Control</th>
<th>Exercise</th>
<th>Recovery*</th>
</tr>
</thead>
<tbody>
<tr>
<td>b/min (HR)</td>
<td>Sitting</td>
<td>Standing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>Stage 1</td>
<td>Stage 2</td>
</tr>
<tr>
<td></td>
<td>77</td>
<td>1.7MPH</td>
<td>12%</td>
</tr>
<tr>
<td></td>
<td>86</td>
<td>3'</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>13</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>%Δ(c)</td>
<td>+15</td>
<td>+26</td>
</tr>
<tr>
<td></td>
<td>PΔ(c)</td>
<td>0.055</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

MPH = miles per hour; ' = minutes; SD = standard deviations; SE = standard error; %Δ(c) = percent change from control; PΔ(c) = significance of change from control.

*Recovery measurements at 2', 5' and 10' are compared to sitting control. All other measurements are compared to standing control.

Table 2—Responses During Treadmill Exercise and Recovery

<table>
<thead>
<tr>
<th>Pre-exercise Period</th>
<th>Control</th>
<th>Exercise</th>
<th>Recovery*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sitting (PEP) msec</td>
<td>Stage 1</td>
<td>Stage 2</td>
<td>Stage 3</td>
</tr>
<tr>
<td>Mean</td>
<td>106</td>
<td>111</td>
<td>82</td>
</tr>
<tr>
<td>SD</td>
<td>10</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>SE</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>%Δ(c)</td>
<td>-26</td>
<td>-26</td>
<td>-33</td>
</tr>
<tr>
<td>PΔ(c)</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Abbreviations: See key to Table 1.

*Recovery measurements at 2', 5' and 10' are compared to sitting control. All other measurements are compared to standing control.

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Cardiac responses during uninterrupted treadmill exercise.


### Table 3—Responses During Treadmill Exercise and Recovery

<table>
<thead>
<tr>
<th>LVET msec</th>
<th>Control Sitting</th>
<th>Exercise Stage &quot;½&quot; 1.7 MPH 5%, 3'</th>
<th>Exercise Stage 1 1.7 MPH 10%, 6'</th>
<th>Exercise Stage 2 2.5 MPH 12%, 9'</th>
<th>Exercise Stage 3 3.4 MPH 14%, 12'</th>
<th>Exercise Stage 4 4.2 MPH 16%, 15'</th>
<th>Exercise Stage 5 5.0 MPH 18%, 18'</th>
<th>Standing Immediate +2 min +5 min +10 min</th>
<th>Sitting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>258</td>
<td>226</td>
<td>244</td>
<td>235</td>
<td>218</td>
<td>200</td>
<td>189</td>
<td>172</td>
<td>174</td>
</tr>
<tr>
<td>SD</td>
<td>31</td>
<td>18</td>
<td>29</td>
<td>29</td>
<td>23</td>
<td>21</td>
<td>9</td>
<td>21</td>
<td>15</td>
</tr>
<tr>
<td>SE</td>
<td>9</td>
<td>5</td>
<td>8</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>%Δ(c)</td>
<td>+8</td>
<td>+4</td>
<td>-4</td>
<td>-12</td>
<td>-16</td>
<td>-24</td>
<td>-23</td>
<td>-22</td>
<td>-10</td>
</tr>
<tr>
<td>Δ(c)</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.003</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.025</td>
</tr>
</tbody>
</table>

**Abbreviations:** See key to Table 1.

*Recovery measurements at 2', 5' and 10' are compared to sitting control. All other measurements are compared to standing control.

sharp to 5' of recovery, though still below sitting control (231 msec vs 258 msec; P = .025). At 10' LVET (247 msec) was not statistically different from sitting control.

### Ejection Time Index

Like PEP, ETI showed a bimodal response (Fig 1 and Table 4). It rose sharply and significantly in the first three minutes of exercise. For the next two stages (up to 9') it remained stable but thereafter increased nearly from 380 msec at the 18' end-point; immediate post-exercise ETI (384 msec) was not significantly different. At all these points ETI differed from the 330 msec standing control (P < .001 each). By 2' sitting recovery it was not significantly different from sitting control (351 msec).

### PEP/LVET

At all points during exercise, PEP/LVET differed significantly from standing control (PΔc < 0.001). It fell immediately and significantly (from 0.49 to 0.34) by 3' exercise (P < .001). It decreased further only to 0.29 at 18'. An abrupt post-exercise rise from 0.29 to 0.34 was not statistically significant.

During sitting recovery PEP/LVET rose more gradually than the other measurements (Fig 1). By 2' recovery it was not significantly different from sitting control (Table 5).

### DISCUSSION

Directional responses during uninterrupted treadmill exercise and recovery were quite comparable to the general pattern during various protocols of uninterrupted bicycle exercise in which systolic time intervals were measured.7-11,18 Thus, heart rate rose smoothly during exercise and fell precipitously in early recovery followed by more gradual restitution toward control levels. Prejection period fell, consistent with both the adrenergic effects and increased preload (increased venous return) due to exercise.10,13,17 However, its pattern was bimodal due to a plateau (82 msec) between 3 and 6 minutes. Ejection time index rose sharply during early exercise, plateaued between 3' and 9', then rose gradually between 9' and 18'; during early recovery it fell precipitously, paralleling the heart rate change (Fig 1). Rises in ETI nearly always imply increased stroke volume, particularly since ejection...
rate increases during exercise\(^{16}\) (i.e., if stroke volume did not increase, the increased ejection rate by itself would decrease the ETI). The initial rise in ETI is characteristic of early upright exercise.\(^8\) The late secondary rise in ETI is a new observation.

The ratio PEP/LVET fell immediately as expected\(^{16}\) and then tended to almost “bottom out” with a slight and very gradual fall from the end of the first 3' stage to end-exercise.

PEP/LVET is a convenient net expression of cardiac function with a variable negative correlation with ejection fraction.\(^2,19\) Since ejection fraction rises during exercise, the fall in PEP/LVET may be an expression of this phenomenon, its pattern suggesting near-maximal change early on. Alternatively, a “mechanistic” explanation is possible. That PEP/LVET approached a floor value relatively early has been previously observed during early bicycle exercise.\(^{19}\) Since a ratio is in itself an artificial construct (i.e., it is not an independent datum), it minimizes similar trends in the numerator and denominator. Figure 1 shows only slightly divergent PEP and LVET curves through much of the exercise period (NB—in the figure PEP and LVET are scaled differently). For the ratio, PEP/LVET, comparable trends of its components explain the slight changes after the large early change.

Left ventricular ejection time is ordinarily not considered separately from heart rate. However, there have been inconsistencies in the reported behavior of LVET during early exercise.\(^5,20\) Figure 1 shows a “paradoxical” rise in mean LVET in the first three minutes. This initial rise in LVET was not statistically significant only because of different responses by different subjects: nine subjects increased, three subjects decreased their LVETs. These observations document individual variability in the early response of this parameter, reconciling differences between previous observers.\(^20\)

### Bimodal Response Patterns

The bimodal response curves of both PEP and ETI feature respective plateaus at three to six minutes and three to nine minutes (Fig 1). Thereafter, both measurements resumed their typical exercise-related directions of change. Any explanation must remain speculative, physiologic factors which could account for simultaneous stability of both PEP and ETI between 3' and 6' would be stable preload and stroke volume. This suggests that the elevation of the treadmill from 5° to 10° without changing the speed did not impose a stress equal to subsequent changes in both speed and elevation.

### Comparison with Bicycle Exercise

Previous studies with bicycle exercise show similar directions of change of heart rate and systolic time intervals.\(^7,11,18\) Comparable subjects who exercised for four minutes at a 150 watt load reached a heart rate of 157 beats per minute.\(^7\) This corresponds to the rate reached at 15' of the present protocol (156 b/min). These can be considered reasonable for comparison because heart rate is one index of the net stress imposed by exercise on the heart.\(^7,11,22\) Table 6 shows that they were indeed comparable. The mean responses are remarkably similar: pre-ejection period was identical, ejection time index was only 7 msec higher on the bicycle and PEP/LVET was only 0.01 less on the bicycle.

### Table 6—Treadmill vs Bicycle Exercise to Same Heart Rate (Mean Measurements ± SE)

<table>
<thead>
<tr>
<th>Protocol</th>
<th>HR</th>
<th>PEP (msec)</th>
<th>ETI (msec)</th>
<th>PEP/LVET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treadmill (Mod Bruce)</td>
<td>156±5</td>
<td>56±3</td>
<td>378±6</td>
<td>0.30±0.02</td>
</tr>
<tr>
<td>Bicycle—</td>
<td>150 W</td>
<td>157±5</td>
<td>56±2</td>
<td>385±5</td>
</tr>
</tbody>
</table>
Responses During Recovery

With the exception of the abrupt increase in pre-ejection period, immediate recovery while still standing showed insignificant changes from the preceding final exercise beats. The subsequent rapid rates of restitution toward control for heart rate and ETI and the relatively gradual rates of restitution of PEP and PEP/LVET were as expected from results with recovery after bicycle exercise.11

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