Usefulness of a Novel Ultrasound Transducer for Continuous Monitoring Treadmill Exercise Echocardiography to Assess Coronary Artery Disease

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**Background** The feasibility of a novel ultrasound probe, which can be attached to the left ventricular (LV) apex chest wall and allows free rotation around its long axis direction for the continuous monitoring of LV wall motion, was tested.

**Methods and Results** There were 36 subjects who had coronary artery disease (CAD). By attaching a novel ultrasound probe to the chest wall, the LV apical views were recorded during treadmill exercise echocardiography (Echo). The continuous monitoring of LV wall motion was satisfactorily feasible in 30 of 36 patients. The visualization rate of the overall LV segments was higher at rest (90%) compared to that during peak exercise (77%). The segments were better visualized in apical portions (90–100%) than in mid (77–96%) or basal portions (68–87%). The sensitivity, specificity, and accuracy for detecting CAD were 61, 100 and 77%, respectively. The wall motion score index 3 and 6 min after exercise decreased significantly compared to those at peak exercise. The number of segments with dysynergy was highest at the peak exercise. Ischemic ST-T depression on electrocardiography was observed only at peak stress periods.

**Conclusions** Continuous monitoring treadmill exercise Echo using a novel ultrasound probe seems feasible for the non-invasive and physiological assessment of CAD. (Circ J 2006; 70: 1297–1302)

**Key Words:** Coronary artery disease; Stress echocardiography; Treadmill exercise test

Treadmill exercise stress is the most common form of stress echocardiography (Echo)1. During exercise on a treadmill, more muscle groups are recruited compared with exercise on a bicycle, and many adults are more familiar with this type of exercise. A higher workload and greater maximal heart rate are typically achieved with this exercise;2–5 however, the principal problem with treadmill exercise stress Echo is the inability to evaluate images during the procedure.1 Treadmill exercise stress Echo diagnosis is usually performed by comparing Echo images obtained in the recumbent position before and after upright exercise.6–11

Many reports on bicycle stress Echo have indicated that the frequency of wall motion abnormality is higher when imaging is performed at the peak rather than after the exercise period.12–15 In addition, Peteiro et al obtained trans-thoracic Echo images at peak exercise using a treadmill and reported the accuracy of peak treadmill exercise Echo compared with post-treadmill exercise Echo.16–18

We developed a novel ultrasound probe, which can be attached to the left ventricular (LV) apex chest wall and allows free rotation around its long axis. Our new transducer might visualize multiple LV apical views and be useful for the continuous monitoring of LV wall motion during treadmill exercise. The purpose of this study was to test the feasibility of this novel ultrasound probe in visualizing multiple LV apical views and in assessing coronary artery disease (CAD) during, at peak, and after treadmill exercise.

**Methods**

**Study Subjects**

The study group consisted of 36 consecutive patients (30 men and 6 women) with suspected or known CAD. Their mean age was 61±12 years (range: 26 to 76 years). Twenty-eight patients had normal LV wall motion on the rest Echo. Eight patients had a prior myocardial infarction documented by history, serial electrocardiogram and serum cardiac enzyme changes. The existing medication included long-acting nitrates in 24 patients (67%), calcium channel-blocking agents in 20 patients (56%), angiotensin-converting enzyme inhibitors in 10 patients (27%) and Î±-adrenergic blocking agents in 1 patient (4%). Medical therapy was continued before stress testing. All patients provided written informed consent to participate in the study and the protocol was approved by the review board of our hospital.

**Novel Transducer and Continuous Monitoring Echo**

The 3.5 MHz transducer was mounted on a spherical external housing with 4 rectangular harnesses. The transducer cable was longer and thinner than usual cable and it was...
therefore easy to attach to and monitor the chest wall. The harnesses were attached and fixed at the LV apical portion on the chest wall of a patient in a standing position using 2 rubber belts (Figs 1, 2). The transducer could be directed freely in any direction to better visualize the LV apical image. It was fixed in an appropriate direction by adjusting the 2 screws, and the transducer could be rotated manually from 0 to 360 degrees around its long axis (Fig 1). The transducer was interfaced with a commercially available ALOKA 5500 ultrasound system (Aloka Corp, Tokyo, Japan).

Study Protocol

Baseline blood pressure, 12-lead electrocardiography and 2-dimensional Echo data were obtained from patients in a standing position. Patients were encouraged to undergo a modified Bruce treadmill exercise test. Exercise was terminated in the presence of new or worsening dysynergy, more than 2 mm depression of ST-segment shift, reaching >85% age-predicted maximal heart rate, severe hypertension (systolic blood pressure >240 mmHg), severe hypotensive response (decrease from baseline >20 mmHg), chest pain or leg fatigue. Heart rate, blood pressure and 12-lead electrocardiography were recorded every 3 min. We diagnosed that the exercise electrocardiographic test was positive for myocardial ischemia if there was horizontal or downsloping ST-segment depression of ≥1 mm at 80 ms after the J point.

The LV apical 4-chamber, long axis and 2-chamber views were imaged by a physician rotating the transducer manually and the images were recorded on S-VHS videotape during and after exercise (Fig 2). The patients were asked to walk quickly with their chest out and the position of the transducer was slightly adjusted by the physician to better visualize the LV apical images. Representative echocardiograms at the baseline, 3 min before peak stress, at peak stress, and 6 min after peak stress were arranged on a digital quad screen using an off-line PROSORB system® Cardiovascular 3.0 (Problem Solving Concepts Inc, Indianapolis, USA). The LV was divided into 16 segments according to the American Society of Echocardiography recommendations19,20. The wall motion of individual segments was assessed and scored by using a 5-point grading system (1=normal, 2=hypokinetic, 3= akinetic, 4=dyskinetic, and 5=aneurysmal).19 The wall motion score index was calculated as the sum of the scores divided by the number of segments evaluated. Positive exercise Echo was defined when new or worsening wall motion abnormalities occurred in at least 1 segment, isolated abnormalities of the inferior basal or septal basal segment during exercise were exceptions21. Two investigators independently analyzed the Echo LV segments by direct side-by-side comparison of the images, with an interobserver agreement of 95% (167 of 176 segments). The sensitivity, specificity, and accuracy of coronary artery stenosis detection were assessed using the Echo and electrocardiography obtained at the baseline and during exercise.

To assess the time-course of the ischemic event, the wall motion score index, ST-segment shift and heart rate were analyzed at the baseline, 3 min before peak stress, peak stress, and 3 and 6 min after peak stress in patients with an ischemic response. Both digitized and videotape images were used for Echo interpretation. To assess the feasibility of our method, the number of LV segments analyzed at each stage was also evaluated. The visualization of 12 or more LV segments throughout the procedure was defined as successful recording.
All patients underwent a coronary angiography within 1 week after exercise treadmill Echo. The severity of coronary artery stenosis was assessed quantitatively and CAD was defined as >50% narrowing compared with the normal lumen diameter in at least 1 coronary artery or major branch.22,27

Statistical Analysis
The data were expressed as the mean±SD. The sensitivity, specificity and accuracy were calculated according to standard formulas. One-way analysis of variance was used to analyze the repeated measurements, and the Tukey’s test was used to examine the significance of differences among continuous values. Differences were considered statistically significant at p<0.05.

Results

Exercise Testing
All patients completed the entire protocol. The reason for termination was new or worsening wall motion abnormality in 11 patients, attaining target heart rate in 6 patients, and leg fatigue in 19 patients. The heart rate, systolic blood pressure and rate-pressure product increased significantly at peak stress compared with other stages (Table 1). There was no chest pain or jeopardized arrhythmia during treadmill exercise.

Feasibility of Continuous Monitoring Treadmill Stress Echo
During the present study, more than 12 LV segments were satisfactorily recorded continuously in 30 of 36 patients (83%), except for 3 obese men, 2 women with large breasts, and 1 man with chronic obstructive pulmonary disease. In these 30 successful recordings, the number of

### Table 1  Hemodynamic Changes During Continuous Monitoring Treadmill Stress Echocardiography

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>3 min before peak</th>
<th>Peak exercise</th>
<th>3 min after peak</th>
<th>6 min after peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systolic BP (mmHg)</td>
<td>133±19</td>
<td>164±33**</td>
<td>173±41**</td>
<td>167±17**</td>
<td>167±17**</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>75±10</td>
<td>108±10**</td>
<td>129±26**</td>
<td>89±14*</td>
<td>85±13</td>
</tr>
<tr>
<td>Rate pressure product (x10³) (mmHg·beats/min)</td>
<td>10.0±1.9</td>
<td>18.0±4.4**</td>
<td>22.3±6.0**</td>
<td>14.9±3.2**</td>
<td>14.3±2.8**</td>
</tr>
</tbody>
</table>

*p<0.05, **p<0.01 vs baseline.
BP, blood pressure.

### Table 2  Number of Segments Visualized During Continuous Monitoring Stress Echocardiography in Patients With Successful Recording

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>3 min before peak</th>
<th>Peak exercise</th>
<th>3 min after peak</th>
<th>6 min after peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>All segments</td>
<td>432/480 (90%)</td>
<td>403/480 (84%)</td>
<td>369/480 (77%)</td>
<td>394/480 (82%)</td>
<td>446/480 (93%)</td>
</tr>
<tr>
<td>Basal segments</td>
<td>146/180 (81%)</td>
<td>149/180 (83%)</td>
<td>122/180 (68%)</td>
<td>138/180 (77%)</td>
<td>156/180 (87%)</td>
</tr>
<tr>
<td>Mid segments</td>
<td>167/180 (93%)</td>
<td>144/180 (80%)</td>
<td>138/180 (77%)</td>
<td>144/180 (80%)</td>
<td>173/180 (96%)</td>
</tr>
<tr>
<td>Apical segments</td>
<td>120/120 (100%)</td>
<td>109/120 (91%)</td>
<td>108/120 (90%)</td>
<td>108/120 (90%)</td>
<td>120/120 (100%)</td>
</tr>
</tbody>
</table>
visualized segments was 432 of 480 (90%) at the baseline, 403 of 480 (84%) at 3 min before peak stress, 369 of 480 (77%) at peak stress, 446 of 480 (93%) at 6 min after peak stress. The segments tended to be visualized better in apical portions (90–100%) compared to mid (77–96%) or basal portions (68–87%) (Table 2).

**Coronary Angiography**

One-vessel disease, 2-vessel disease and 3-vessel disease were seen in 8, 9, and 7 patients, respectively.

**Diagnostic Utility**

The overall sensitivity, specificity and accuracy for detecting CAD were 61% (11 of 18), 100% (12 of 12) and 77% (23 of 30), respectively, in patients who had satisfactory recordings. The sensitivity in detecting multiple vessel disease was 69% (9 of 13). An example of ischemic response observed in a patient with left anterior descending CAD is shown in Fig. 3. The sensitivity, specificity, and accuracy of treadmill stress electrocardiography for the detection of CAD were 39% (7 of 18), 67% (8 of 12) and 50% (15 of 30), respectively.

**Time-Course of Monitored Variables in Patients With Ischemia**

The time-course of the wall motion score index, ST-segment shift and heart rate in 11 patients with positive exercise echocardiography are shown in Figs 4 and 5. The wall motion score index was significantly increased at peak stress compared to at all other stages. The index at 3 min before peak stress was significantly increased compared to the baseline. The index at 3 min after peak stress was also significantly increased compared to at 6 min after peak stress. The ST-segment depression was ≥1 mm at peak stress, indicating that the ECG did not detect myocardial ischemia at those stages.

**Discussion**

We showed that continuous monitoring of LV wall motion was feasible in most patients (83%) during treadmill exercise using our novel transducer. More than 90% of the overall LV segments were satisfactorily visualized at rest; however, the percentage of visualized LV segments decreased to 77% during peak exercise. The segments were better visualized in apical portions (90–100%) than in mid (77–96%) or basal portions (68–87%) both during exercise and at rest. Failure of this novel approach was limited to
Novel Transducer for Treadmill Exercise Echo

17% of patients who were obese, or had large breasts or pulmonary disease. LV monitoring was difficult when patients were running in a bending forward position, probably because of the narrowing of the echo window. They were therefore asked to walk quickly with their chest out. A slight adjustment of the transducer position was necessary to better visualize LV apical images. The diagnostic utility of this method was reasonable with sensitivity, specificity, and accuracy being 61, 100, and 77%, respectively.

Chandraratna et al reported the feasibility of continuous transthoracic imaging of LV wall motion in a sitting up, supine or left lateral position using their ultrasound transducer (CONTISON), which was spherical and was mounted on an external housing to permit 360° rotation within one plane. They also reported continuous transthoracic ultrasonic monitoring of balloon valvuloplasty, pulmonary artery diastolic pressure and cardiac output or pericardiocentesis using the CONTISON transducer; however, they did not apply their transducer to patients during treadmill exercise. We could visualize multiple LV apical views using our continuous monitoring transducer, which was different from the CONTISON transducer as it was mounted on a hemispherical external device to permit free rotation in any direction. In the present study, once the direction of the transducer to visualize LV apical images was determined, the direction was fixed using 2 screws and was able to rotate freely around the transducer axis.

The present study confirmed the utility of continuous monitoring Echo to evaluate CAD during a treadmill exercise test. The sensitivity in the present study was lower (61 vs 71–80%) than that for a previously reported treadmill exercise Echo. In contrast, the sensitivity was similar (69%) in multi-vessel disease compared with other reports on treadmill exercise Echo. The sensitivity of detecting single-vessel disease was low (40%), possibly because 6 patients did not reach the target heart rate and therefore the exercise was submaximal in these patients. After the exclusion of these 6 patients, the overall sensitivity was 79% (11 of 14). Other possible reasons for this low sensitivity might be: (1) coronary artery stenosis criteria of only 50% or more for diameter stenosis; (2) the lack of parasternal long- and short-axis views; (3) the lack of second harmonic imaging; and (4) the continuation of medical therapy before treadmill testing.

Test verification bias has been noted in exercise Echo with higher sensitivity and lower specificity results. Verification bias occurs when the result of exercise Echo is used to decide which patients will receive the verification test because the reader may interpret the Echo images more aggressively to maintain higher sensitivity. In the present study, the indication of coronary angiography was determined independently of the results of exercise Echo; however, we might have been conservative in our image interpretation because we had no false-positive patients.

Few reports have observed the ischemic cascade during human treadmill exercise Echo. LV dyssynergy caused by myocardial ischemia was observed 3 min before peak stress and continued until 3 min after peak stress in the present study. However, the number of segments with LV dyssynergy was highest at the peak exercise, suggesting the usefulness of peak exercise stress Echo. In contrast, ischemic ST-T depression was observed only at peak stress. These findings confirmed the ischemic cascade in which ischemic LV dysfunction is followed by electrocardiographic changes. Our data also showed that ischemic LV dysfunction recovered later than electrocardiographic changes, and LV dysfunction was observed with a heart rate less than the target. This longer duration of LV wall motion abnormality and the frequent development of LV wall motion abnormality with a lower heart rate less than the target suggests the utility of continuous monitoring of LV wall motion abnormality during the treadmill exercise test.

LV dyssynergy finally disappeared 5 min after peak stress in the present study. Dugianti et al reported that the duration of LV wall motion abnormalities was 71 to 81 s by supine bicycle Echo. In contrast, Robertson et al reported that LV wall motion abnormalities persisted for at least 30 min in patients with severe CAD (stunned LV myocardium after exercise treadmill). These differences in recovery time of LV dysfunction may be caused by differences in the duration and severity of myocardial ischemia in each study.

Clinical Implications and Limitations

Continuous monitoring of treadmill stress Echo is a safe stress test because it provides LV wall motion information throughout the test and the test can be terminated before chest symptoms or significant electrocardiographic changes develop. It will be useful in patients with severe CAD to prevent a severe ischemic response. It can also be useful for the assessment of patients with syndrome X, in whom wall motion abnormalities were not observed despite chest pain and ECG changes during stress Echo.

In the present study, the effect of vasospasm on the LV wall motion was not investigated. Ergonovine stress Echo, in which clear echocardiographic evidence was obtained during stress, has been reported to be useful in assessing LV wall motion in patients with vasospasm. The number of patients examined was small and so future studies should involve more patients.

Conclusions

Continuous monitoring treadmill exercise Echo, using a novel ultrasound probe, seems feasible and useful for the non-invasive and physiological assessment of CAD.

References

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