Continuous Ambulatory Radionuclide Monitoring of Left Ventricular Function: Effect of Body Position During Ergometer Exercise

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We assessed the reliability of a continuous ambulatory radionuclide monitoring system (the VEST system, Capintec, Inc., Ramsey, NJ) for measurement of left ventricular performance during exercise in the upright and supine positions. **Methods:** Sixteen healthy male volunteers (aged 32–46 yr; mean age 37 ± 4 yr) were studied. All volunteers underwent ergometer exercise testing in both the upright and supine positions, and left ventricular performance was determined with the VEST system. **Results:** The resting heart rate, systolic blood pressure, pressure rate product, relative end-diastolic volume, relative end-systolic volume and left ventricular ejection fraction (LVEF) all showed no differences between the upright and supine positions. At peak exercise, the heart rate, systolic blood pressure and pressure rate product showed no differences between the upright and supine positions. In the upright position at peak exercise the relative end-diastolic volume was increased (83% ± 9% to 91% ± 11%, $p < 0.001$); the relative end-systolic volume remained unchanged (34% ± 3% to 33% ± 15%), and LVEF was significantly increased from 58% ± 6% to 66% ± 11% ($p < 0.01$). In the supine position at peak exercise, the relative end-diastolic volume remained unchanged (85% ± 5 to 83% ± 7%), the relative end-systolic volume was increased (35% ± 5% to 43% ± 13%, $p < 0.01$), and LVEF was decreased from 58% ± 5% to 48% ± 17% ($p < 0.01$). These results indicated inferior data collection by the VEST system in the supine position. **Conclusion:** Since the detector of the VEST system may be too small, the data collection is impaired during exercise in the supine position by shifting the heart with deep respiration. The VEST system is very useful for determining left ventricular performance when applied in the sitting or upright position. However, in the supine position during exercise, the use of the VEST system should be avoided because it might indicate an artifactual deterioration of left ventricular performance.

Key Words: ambulatory radionuclide monitoring; left ventricular ejection fraction; exercise

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A continuous ambulatory radionuclide monitoring system (the VEST system, Capintec, Inc., Ramsey, NJ) was recently developed based on ^{99m}Tc radionuclide angiography. This system makes it possible to measure real-time changes of the left ventricular ejection fraction (LVEF) (*1*). Several reports have indicated that the VEST system is a very useful tool for monitoring the LVEF during stress-tests and silent myocardial ischemia, and for evaluating cardiac function in daily life (*1–8*). It has been reported that the accuracy and reproducibility of the VEST system in determination of left ventricular performance are high enough for it to be used clinically (*9*). However, reports available so far have assessed the accuracy of the VEST system in the sitting or upright position, and there have been few studies on its value in the supine position. In addition, there have been no comparisons of the VEST system between the supine and upright positions. In this study, we used the VEST system to measure left ventricular function in healthy volunteers during ergometer exercise in the upright and supine positions. We found that errors in the measurement of left ventricular performance with the VEST system in the supine position were greater than expected and might lead to an artifactual deterioration of left ventricular function.

MATERIALS AND METHODS

Subjects

The study group consisted of 16 healthy male volunteers (aged 32–46 yr; mean age 37 ± 4 yr) with no history of cardiovascular or pulmonary disease. All subjects were asymptomatic and had a normal physical examinations and 12-lead ECGs at rest. None had a significant ST change in modified lead V_1 V_5 during ergometer exercise in this study. The body height, body weight and body mass index in subjects were 171 ± 4 cm (165–182 cm), 67 ± 9 kg (53–80 kg) and 23 ± 3 kg/m (18–28 kg/m) (*2*). Each subject underwent measurement of left ventricular performance with the VEST system during ergometer exercise in the upright and supine positions. The upright and supine ergometer exercise tests were performed on different days. The mean duration of two ergometer exercises was 14 ± 8 days (5–27 days).

Continuous Monitoring of Left Ventricular Function (VEST)

All subjects underwent electrocardiographic gated equilibrium blood-pool scintigraphy in the supine position. After intravenous injection of 740 MBq ^{99m}Tc-labeled human serum albumin, data acquisition was performed with a single-crystal gamma camera fitted with a low-energy, all-purpose, parallel-hole collimator and interfaced to a dedicated minicomputer in list mode. The left anterior oblique projection that best displayed the interventricular septum was used, i.e., approximately 45° with 10° caudal angulation. After acquisition, the data obtained were organized into an image sequence that separated 20 frames per cardiac cycle in a 64 (64 matrix with a 1.5 zoom). List mode data were recorded until 3000K total counts. The LVEF was computed from the global time-activity curve using a signal semi-automatic LV region of interest (ROI) drawn on the functional phase image. ROIs were drawn automatically. After gated radionuclide angiography, the detector of the VEST system was positioned over the left ventricle under a gamma camera in a left anterior oblique projection such that the left atrium, the right ventricle and the spleen were not covered. A 2-min static gamma camera image was obtained in the supine position to confirm the adequacy of the VEST detector position. The nuclear data collected consisted of sequential gamma counts of the left ventricular blood-pool activity obtained at 32

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TABLE 1
Changes in VEST Measurements of Hemodynamic Parameter During Upright or Supine Ergometer Exercise

	Position	Rest	Exercise
HR (bpm)	Upright	84 ± 13	164 ± 20†
	Supine	76 ± 13	153 ± 20†
SBP (mm Hg)	Upright	119 ± 9	168 ± 11†
	Supine	123 ± 11	176 ± 12†
HR × SBP (×10^3)	Upright	10.0 ± 1.6	17.8 ± 1.8†
	Supine	8.7 ± 2.2	16.4 ± 4.0†
LVEF (%)	Upright	58 ± 6	66 ± 1.1*
	Supine	58 ± 5	48 ± 17*
% EDV	Upright	83 ± 9	91 ± 10†
	Supine	85 ± 5	83 ± 7
% ESV	Upright	34 ± 3	33 ± 14
	Supine	35 ± 5	43 ± 12*

*$p < 0.01$
$^{\dagger}p < 0.001$ from values at rest.
Values are means ± s.d. (n = 16). HR = heart rate; SBP = systolic blood pressure; LVEF = left ventricular ejection fraction; % EDV = relative end-diastolic volume; % ESV = relative end-systolic volume.

times per second. All of the VEST acquisition was undertaken in the supine or upright position on an ergometer machine.

Study Protocol

Relaxation Phase. Each subject was asked to relax for 10 min with comfortable music after placement of the VEST detector. The data derived from these measurements were used to calculate the variability of the VEST-determined ejection fraction at rest.

Ergometer Exercise Phase. After relaxation, each subject underwent symptom-limited upright or supine bicycle ergometer exercise testing. The work load was adjusted to 50 W initially, and was increased by 25 W every 3 min. Exercise was stopped by the supervising physician at the onset of fatigue or severe leg discomfort or at the time of 95%–100% of the age-predicted maximum heart rate.

Data Analysis

After completion of the protocol, the VEST radionuclide data were reviewed for their technical adequacy. The average counts per 31 msec for the entire interval of recording were displayed to identify any significant motion of the detector or any major failure of the device. After this screening test, the radionuclide and ECG data were summed for 15-sec intervals to calculate the LVEF, relative end-systolic and end-diastolic volumes, and heart rate. The LVEF was calculated from the stroke counts divided by the background-corrected end-diastolic counts. Individual VEST background count values were determined as the values necessary to match the initial VEST-determined ejection fraction at rest with that obtained by the gamma camera (*3*). Each respective value was then used throughout the individual's VEST data analysis.

Statistics

Data are expressed as the mean ± s.d. The paired Student's t-test was used to evaluate measurements obtained in the upright and supine positions before and during peak exercise testing. A p value < 0.05 was considered statistically significant.

RESULTS

As shown in Table 1, the heart rate, systolic blood pressure, pressure-rate product, LVEF, relative end-diastolic volume and relative end-systolic volume all showed no differences between the upright and supine positions at rest before ergometer exercise. At peak exercise, the heart rate, systolic blood pressure and pressure-rate product showed no differences between the upright and supine positions. At peak exercise in the upright position, the relative end-diastolic volume was significantly increased (83% ± 9% to 91% ± 11%, $p < 0.001$), the relative end-systolic volume remained unchanged (34% ± 3% to 33% ± 15%), and LVEF was significantly increased from 58% ± 6% to 66% ± 11% ($p < 0.01$). At a similar exercise intensity in the supine position, the relative end-diastolic volume remained unchanged (85% ± 5% to 83% ± 7%), the relative end-systolic volume was increased (35% ± 5% to 43% ± 13%, $p < 0.01$), and LVEF was significantly decreased form 58% ± 5% to 48% ± 17% ($p < 0.01$).

Figure 1 showed a representative VEST record obtained in a 34-yr-old subject. During ergometer exercise in the upright position, the heart rate gradually increased. At the same time, the relative end-diastolic volume increased, the relative end-systolic volume decreased, and LVEF increased significantly from 67%–79%. On the other hand, during ergometer exercise in the supine position, the heart rate increased, the relative end-diastolic volume unchanged, the relative end-systolic volume increased, and LVEF decreased markedly from 63%–38%, showing impaired data collection by the VEST system.

DISCUSSION

In this study, measurements of left ventricular performance obtained during ergometer exercise using the VEST system were noticeably different between the upright and supine positions. In particular, the left ventricular performance of healthy volunteers was decreased in the supine position, which is totally inconsistent with previous reports. Many researchers have already reported on a difference in left ventricular performance during ergometer exercise in the supine and upright positions as assessed with a thermodilution catheter (*10*), echocardiography (*11*) and radionuclide angiography (*12,13*). These reports indicated a slight difference in hemodynamics between the upright and supine positions, but LVEF increased during exercise regardless of the position. These findings suggest that measurement of exercise left ventricular performance with the VEST system might face some problems. Previous VEST studies on left ventricular performance during exercise or daily life have been performed in the sitting or upright position, with few studies being available on the supine position (*14,15*). In particular, there are no reports on exercise measurements with the VEST system in the supine position.

Poliner et al. (*12*) performed radionuclide angiography in healthy subjects and found that the resting end-diastolic volume was 26% greater in the supine position than in the upright position, while end-systolic volume was similar in both positions and LVEF was slightly greater in the supine position. During peak ergometer exercise in the supine position, they found that the end-diastolic volume was 27% higher than the resting level, while the end-systolic volume remained unchanged and LVEF was increased by 11% (*12*). On the other hand, at peak exercise in the upright position, end-diastolic volume was 39% higher than the resting level but lower than in the supine position. In addition, end-systolic volume was 41% lower than the resting level and was also lower than in the supine position. In contrast, they found that LVEF was increased by 26% and was greater than in the supine position (*12*). These findings regarding exercise left ventricular performance in the supine and upright positions are in good agreement with those reported by Freeman et al. (*13*).

Our measurements obtained with the VEST system showed that at peak exercise in the upright position, relative end-diastolic volume was increased, relative end-systolic volume was unchanged, and LVEF was increased. On the other hand, at

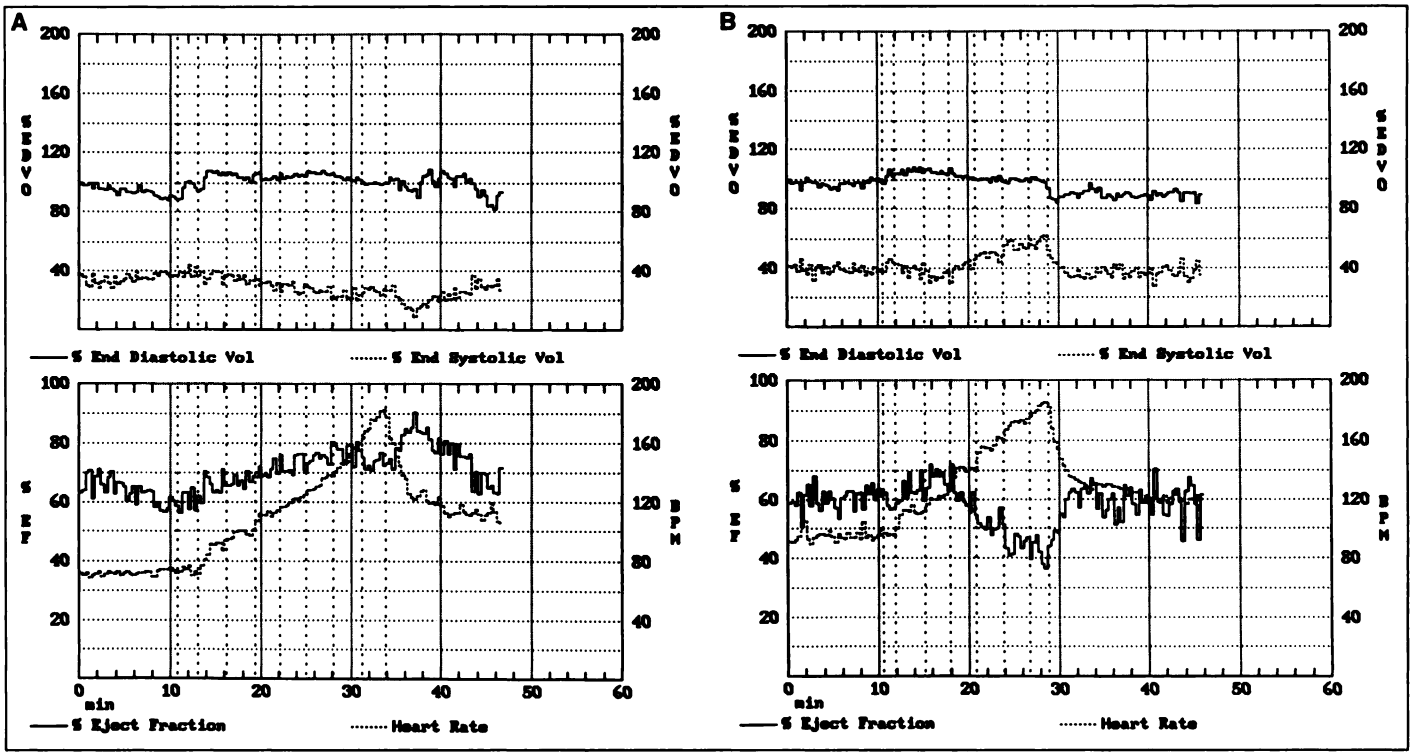

FIGURE 1. A representative record of the VEST system in a 34-yr-old normal subject. (A) During ergometer exercise in the upright position, the heart rate gradually increased. At the same time, the relative end-diastolic volume increased, the relative end-systolic volume decreased, and LVEF increased significantly from 67%–79%. (B) In the supine position, the heart rate increased, the relative end-diastolic volume unchanged, the relative end-systolic volume increased, and LVEF decreased markedly from 63%–38%, showing impaired data collection by the VEST system.

peak exercise in the supine position, relative end-diastolic volume was unchanged, relative end-systolic volume was increased, and LVEF was decreased as a result. In light of the results obtained so far with previous reports of radionuclide angiography (*12,13*), these findings suggest that the VEST detectors failed to collect data accurately from the left ventricle during ergometer exercise in the supine position.

There are several possible causes of impaired data collection by the VEST system. One of the most likely causes of impaired data collection during supine exercise is respiratory movement. Respiratory movement increases with the increasing intensity of exercise, and the vertical motion of the diaphragm becomes greater than at rest. In the supine position, the diaphragm is pushed up towards the thoracic cavity by the abdominal organs. For this reason, exercise in the supine position causes the diaphragm to shift the heart markedly in association with abdominal respiration. Conventional radionuclide angiography collects data from the whole heart including the lung fields. However, the VEST radionuclide detector is only 6.5 cm in diameter and might not cover the shifts of the heart resulting from respiratory motion, thus failing to collect accurate data from the left ventricle. In the upright position, thoracic respiration is predominant and the diaphragm shifts downward together with the abdominal organs. Therefore, the vigorous respiration associated with exercise does not cause a marked shift in the position of the heart, and the small VEST radionuclide detector can still collect appropriate data. To prove our hypothesis, gamma camera images at end-expiratory phase and end-inspiratory phase were obtained to confirm the relationships between the detector and the heart position. The gamma camera image in the upright position did not show a significant change in the detector location between end-expiratory phase (Fig. 2A) and end-inspiratory phase (Fig. 2B). On the other hand, in the supine position, the detector was located on the center of the LV at end-expiratory phase (Fig. 2C), while detector shifted to the outflow tract of the LV and the aortic root at end-inspiration phase (Fig. 2D). Thus, it is reasonable to speculate that, when the detector collects the nuclear data from the outflow tract of the LV cavity and the aortic root, relative end-systolic volume increases and relative end-diastolic volume remains unchanged.

Another source of differences between the supine and upright

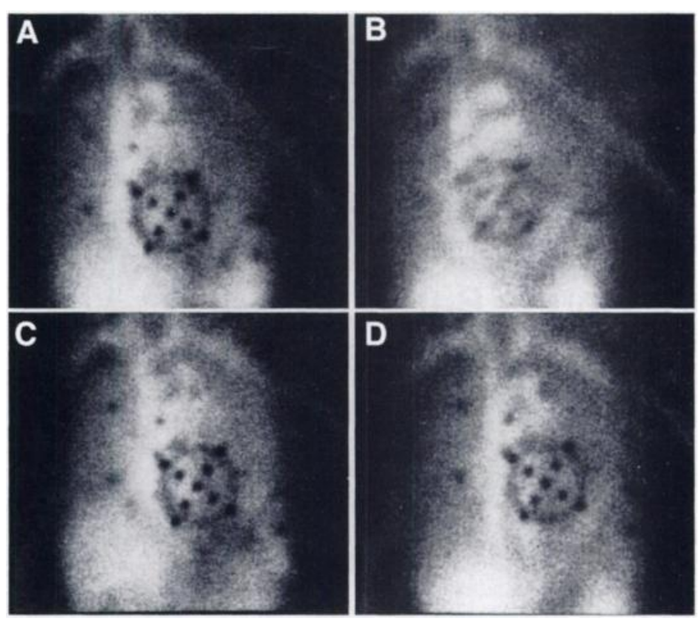

FIGURE 2. A representative record of gamma camera images of the same subject at end-expiratory phase and end-inspiratory phase. (A) The gamma camera image in the upright position did not show a significant change in the detector location between end-expiratory phase and (B) end-inspiratory phase. (C) In the supine position, the detector was located on the center of the LV at end-expiratory phase, while (D) detector shifted to the outflow tract of the LV and the aortic root at end-inspiration phase.

positions could be the method of fixing the VEST detector, since measurement errors may occur if the detector deviates greatly from the set position during exercise. However, movement of the detector should be smaller during supine ergometer exercise as compared to upright exercise, since no positional changes occurred during our study. Therefore, the method of fixing the detector does not appear to provide an the explanation for the observed reduction of LVEF during supine ergometer exercise.

Another source for the discrepancy concern differences in how the background was treated. When the LVEF is computed from data in the left ventricular region of interest during conventional radionuclide angiography with ^{99m}Tc, the count in a certain region of the lungs is taken as the background activity for data processing (*16*). With the VEST system, however, a certain proportion of the left ventricular end-diastolic count is always subtracted as the background, so that the average LVEF during a 15-min period at rest is equal to the LVEF measured by radionuclide angiography (*6*). This computation method is based on the premise that the background count changes is proportion to the left ventricular end-diastolic count (*17*). The LVEF may thus be underestimated if the real background increases at peak exercise in the supine position.

The VEST system is a new technique for noninvasive observation of changes in ventricular performance during daily life. However, our study revealed some limitations with respect to assessment of cardiac performance in the supine position. Garpestad et al. (*14,15*) measured supine left ventricular performance in patients with obstructive sleep apnea using the VEST system. According to their report, the blood pressure began to increase after resumption of ventilation after sleep apnea, and at the same time the VEST system revealed a transient increase in LV end-systolic volume and a decrease in cardiac output, i.e., deterioration of cardiac performance. They assumed that these inconsistent findings, i.e., an increase in blood pressure and an increase in LV end-systolic volume on resumption of ventilation might be caused by different physiological responses (*14*). However, it is impossible to rule out an apparent increase in LV end-systolic volume associated with deep respiration in the supine position when using the VEST system. Accordingly, this system should probably not be applied to exercise tests accompanied by deep respiration in the supine position, such as ergometer exercise tests, hyperventilation tests or mental stress tests.

CONCLUSION

The VEST system is very useful when applied in the upright or supine positions at rest. However, in the supine position during the exercise, the VEST system may falsely indicate deterioration of left ventricular performance due to the effect of respiratory motion, and therefore it should not be applied to the measurement of exercise cardiac performance in this position.

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EDITORIAL

Seeing Is Believing

Beat-by-beat determination of myocardial performance offers a means of understanding the physiologic responses of the heart to activities of daily living. In 1976, Wagner et al. (*1*) described an instrument, the nuclear stethoscope, consisting of a collimated sodium iodide detector attached to a multichannel scaler to record a time-activity histogram from the left ventricle after radiolabeling the patient's blood. While the device worked, it was evident from the start that careful localization of the left ventricular blood pool was required to obtain accurate information. A variety of techniques were used to accomplish this task. In the initial article, the authors referred to positioning the left ventricular detector by moving the probe until a maximal count rate was observed and then making minor changes until the maximal stroke volume was obtained. In the commercial version of the instrument, the collimator was changed to a converging mode with a focal point 2 in. in front of the detector and with a special "positioning mode" to assist the operator with this task (*2*). This positioning mode resulted in an improved correlation coefficient when nuclear stethoscope values were compared to those obtained with the gamma camera. A study by Hoilund-Carlsen et al. (*3*) demonstrated the striking changes in ejection fraction caused by slight mispositioning of the detector. Several investigators have had difficulty positioning the probe, and reported poor correlation be-

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