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Ambulatory ventricular function monitoring for serial assessments of cardiac function during exercise

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Summary

An ambulatory ventricular function monitor (VEST) facilitated measuring left ventricular (LV) function, and performing electrocardiography (ECG) in a natural environment. To assess cardiac response to a variety of exercises, LV function was serially recorded for each of 18 normal subjects using a VEST. The VEST detector was fixed over the LV region following the gated blood pool scan, and the beat-to-beat LV time-activity curve and ECG were continuously recorded. After a baseline recording was made with the subject sitting quietly, the subject performed on a bicycle exercise (n=16), on a treadmill (n=14), and by walking up 10~16 flights of stairs (n=18) while wearing the VEST. The beat-to-beat radionuclide data were averaged for 15–30 seconds to calculate ejection fraction (EF), relative end-diastolic (EDV) and end-systolic (ESV) volumes, and the heart rate.

Serial LV function monitoring during each exercise, particularly while walking upstairs and on a treadmill, documented rapid increases in EF during the early stages of exercise, with increases in EDV, decreases in ESV, and no change in EF in the later stages. Heart rate and systolic blood pressure increased progressively with successive stages. The pressure rate product at the peak exercise was highest during treadmill exercise (32,600) and lowest while climbing stairs (24,700). Immediately after exercise, EDV and ESV rapidly decreased and EF increased further, particularly after bicycle and treadmill exercise.

These data demonstrate that the VEST can measure LV function continuously in an ambulatory environment, and that it is an effective means of evaluating normal cardiac physiology during various exercises.

Key words

Radionuclide ventriculography Exercise Ventricular function Ambulatory monitoring

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Introduction

The effect of exercise on left ventricular function has been extensively investigated by means of hemodynamic measurements, contrast angiography, and various non-invasive methods[1~4]. Exercise radionuclide ventriculography has been used to assess normal cardiac responses and cardiac function reserves in various heart diseases[5~9]. Although this technique provides detailed information about left ventricular function, a gamma camera interfaced to a computer cannot readily measure cardiac function under ambulatory conditions. It would be difficult to assess serial cardiac function during dynamic exercises, such as during daily activities, like climbing stairs or during treadmill exercise. To resolve this limitation of the gamma camera, an ambulatory device was developed which is worn like a vest, and can measure left ventricular function continuously while patients carry on their daily tasks[10~13]. A previous study showed excellent correlations of ejection fractions at rest and during exercise with those measured by a gamma camera[11~13]. The present study describes the clinical application of this instrument for assessing cardiac responses in normal subjects during various exercises.

Materials and methods

Subjects

Eighteen healthy volunteers, 11 men and seven women, aged 21 to 39 with a mean age of 30.7 years were studied. There were no histories of chest pain, hypertension or other cardiac disorders. All subjects gave their informed consents.

Instrument

The ambulatory ventricular function monitor (VEST) was used to monitor beat-to-beat left ventricular function and to obtain electrocardiograms (ECG) of each subject[11~13]. The instrument consisted of a NaI main detector, with a parallel-hole collimator over the left ventricle, a cadmium telluride background detector over the lung, and an ECG recorder, batteries and associated electronics in a plastic garment, which was worn like a vest (**Fig. 1**).

This instrument monitored one channel of the ECG, the beat-to-beat left ventricular time activity curves, background counts, and event marks for up to 10 hours (**Fig. 2**). All information was recorded on a modified Holter-type cassette tape, and entered into a minicomputer (PDP 11/73) for analysis and display.

Data acquisition

Following the intravenous administration of stannous pyrophosphate, five ml of the subject's blood was drawn into a heparinized syringe containing 25–30 mCi Tc-99 m pertechnetate. The blood was incubated for 10 min, and cen-

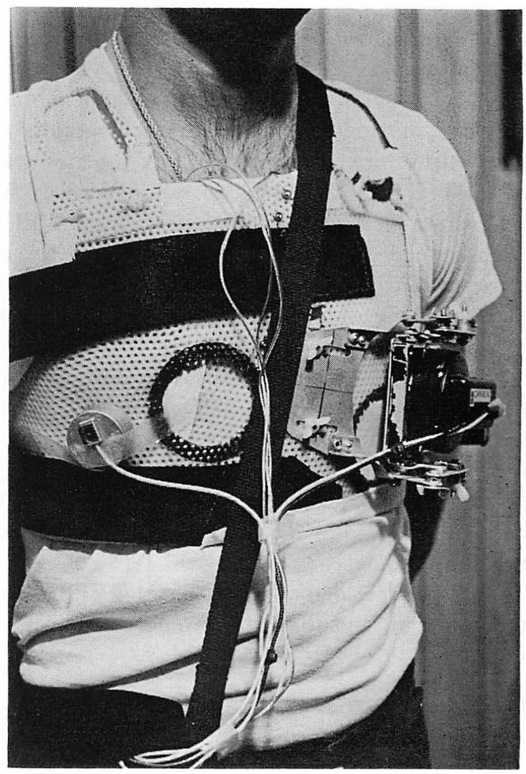

Fig. 1. Ambulatory ventricular function monitor (VEST).

The main radionuclide detector is placed over the region of the left ventricle and the background detector placed over the right lung. All the nuclear data and electrocardiogram are continuously monitored and entered into a modified Holter recording system.

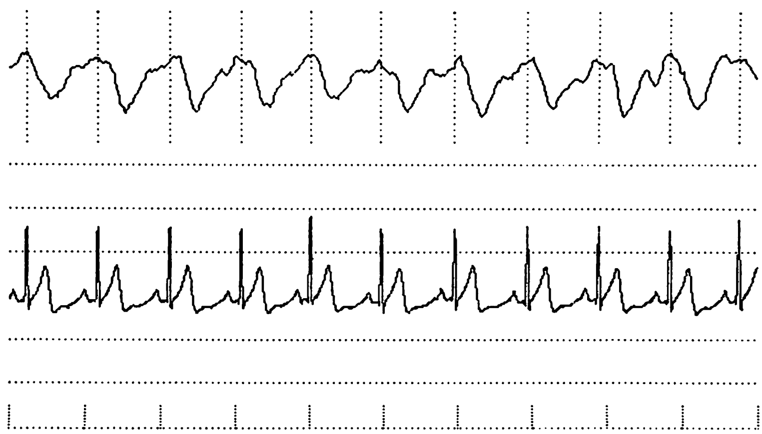

Fig. 2. Beat-to-beat left ventricular time activity curves (top) **and electrocardiogram** (middle) **obtained from the VEST.**

Each vertical line at the bottom represents one second.

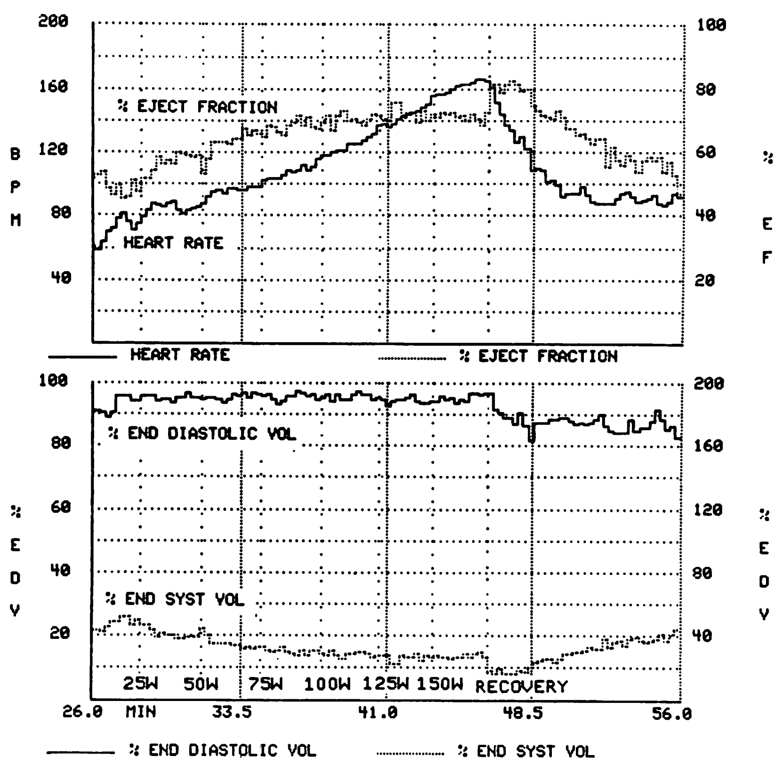

Fig. 3. Changes in left ventricular function in a normal volunteer during graded bicycle exercise.

Changes in ejection fraction (EF), heart rate (top), end-diastolic and end-systolic volumes (bottom) are displayed from 26 to 56 min of recording. EF increases early in the stage of exercise without further increase in the late stage, while heart rate increases steadily.

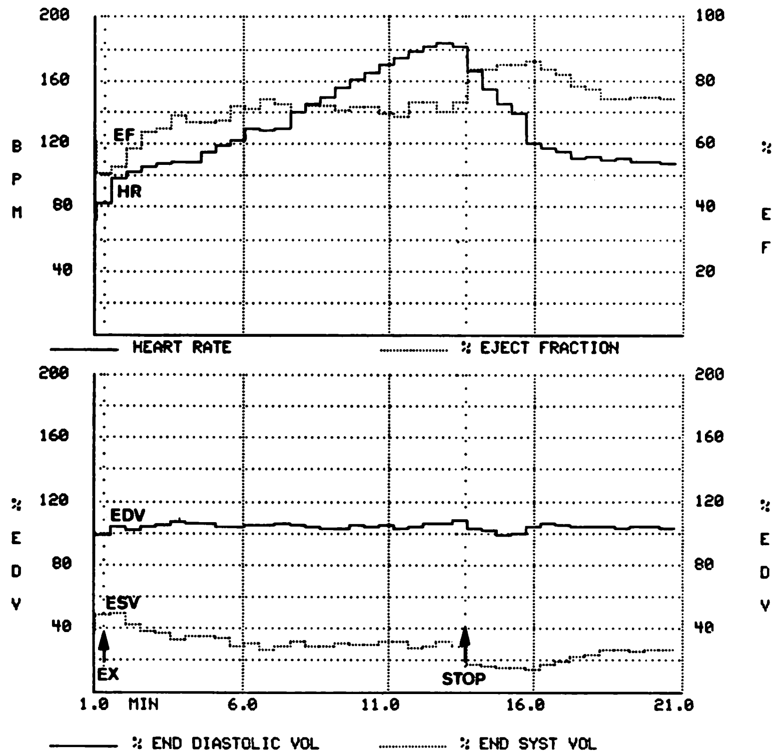

Fig. 4. Changes in left ventricular function in a normal volunteer during treadmill exercise.

Note an early rise in ejection fraction without further increase in the late stage of exercise.

trifuged, the plasma discarded, and the remaining red cells were resuspended in five ml saline. Ten to 20 mCi Tc-99 m-labeled red blood cells were reinjected into the subject for the study.

Gated blood-pool scans were recorded in the anterior and left anterior oblique views using a gamma camera equipped with an all-purpose collimator. On completion of the gated blood pool scans, the main VEST detector was positioned over the patient's left ventricle. The background detector was placed over the right lung field, avoiding the major vessels. The position of the detector was confirmed using 20-sec static images from the gamma camera, and by assessing the position of the silhouette of the main detector over the left ventricular blood pool.

ECG electrodes were placed on the patient's prepared skin to record a modified V_5 ECG lead. The nuclear and ECG data were recorded by the VEST recorder.

Baseline measurements were made with the subject sitting quietly on a chair for 5–10 min. The baseline values were compared with those recorded during various exercises. Subjects stood up and walked in the hallway for 5–10 min, then walked up 10–16 flights of stairs at their usual speed. Sixteen subjects performed graded upright bicycle exercise, starting at 25 watts, then increasing by 25 watt increment every three min, and 14 subjects performed graded treadmill exercise beginning at the stage 0 of the Bruce protocol. Between exercise periods, the subjects rested for at least 30 min. Each sequence of exercise testing was randomly selected. Blood pressure was recorded using a

Table 1. Sequential changes in cardiac function during bicycle exercise (EX), treadmill EX and stairs EX

	Bicycle EX (n=16)				Treadmill EX (n=14)				Stairs EX (n=18)			
	EF	EDV	HR	SBP	EF	EDV	HR	SBP	EF	EDV	HR	SBP
Stage 1	+0.08*	+10%*	+25*	+14*	+0.14*	+10%*	+17*	+13*	+0.09*	+ 9%*	+17*	–
Stage 2	+0.10*	+11%	+41*	+32*	+0.20*	+12%	+32*	+19*	+0.20*	+12%*	+45*	–
Peak	+0.15*	+13%	+79*	+68*	+0.20	+21%*	+86*	+65*	+0.22	+15%*	+65*	+49
Recovery	+0.21*	+ 1%*	+40*	+46*	+0.32*	+ 7%*	+37*	+52*	+0.20	0%*	+34*	–

* $p<0.05$ vs the previous stage.
The value are expressed as changes from the baseline values.

sphygmomanometer.

After completion of the protocols, 20-sec static images were recorded again with the gamma camera to confirm that the VEST detector had not moved during recording[11].

Data analysis

After completion of the recording, each VEST cassette tape was placed in a tape player and the data were entered into a PDP 11/73 computer. Initially, beat-to-beat radionuclide and ECG data were displayed (**Fig. 2**). These data were then summed for 15∼30 sec intervals, and data trends were displayed graphically.

When average counts exceed 600 per 31 millisec, a 15 second R wave synchronized average time activity curve was calculated to measure ejection fraction, heart rate, end-diastolic and end-systolic counts, and relative cardiac output. When average counts were less than 600, a 30 sec average time activity curve was calculated to minimize any statistical fluctuation. Ejection fraction was calculated by dividing the stroke counts by the background subtracted from end-diastolic counts. Initial calibration studies suggested a background of 70% for each end-diastolic counts provided by ejection fraction values with the VEST which best correlated with those measured by the gamma camera[12,13]. Relative end-diastolic volume was expressed as 100% at time zero.

Statistics

Data were expressed as means±standard deviations. For statistical analysis, the Student paired t test was used. A p value less than 0.05 was considered significant.

Results

Representative trend analyses of normal volunteers during bicycle exercise and during treadmill exercise are shown in **Figs. 3 & 4.** For bicycle exercise, baseline ejection fraction was 49% before exercise; and ejection fraction rapidly increased to 70% during bicycle exercise (25∼75 watt) (**Fig. 3**). It did not increase further from 100 to 150 watts, but heart rate increased sequentially to 165 at the peak exercise level. End-diastolic volume increased by 6% during exercise, and end-systolic volume gradually decreased with increases in stroke volumes and ejection fractions. Immediately after exercise, ejection fraction rose to 80% for two min, with decreases in enddiastolic and systolic volumes.

For treadmill exercise, similar changes in cardiac function were observed (**Fig. 4**). Ejection fraction was 50% at baseline, and increased to 70% within the first six min, but did not change during the last seven min, while heart rate increased steadily to 180 at the peak exercise level. Immediately after exercise, further increases in ejection fraction were observed with decreases in end-diastolic and end-systolic volumes.

Cardiac responses to these exercises are summarized in **Table 1** and **Figs. 5∼7.** With each exercise, heart rate and systolic blood pressure increased steadily in each stage. Ejection fraction also increased with mild increases in

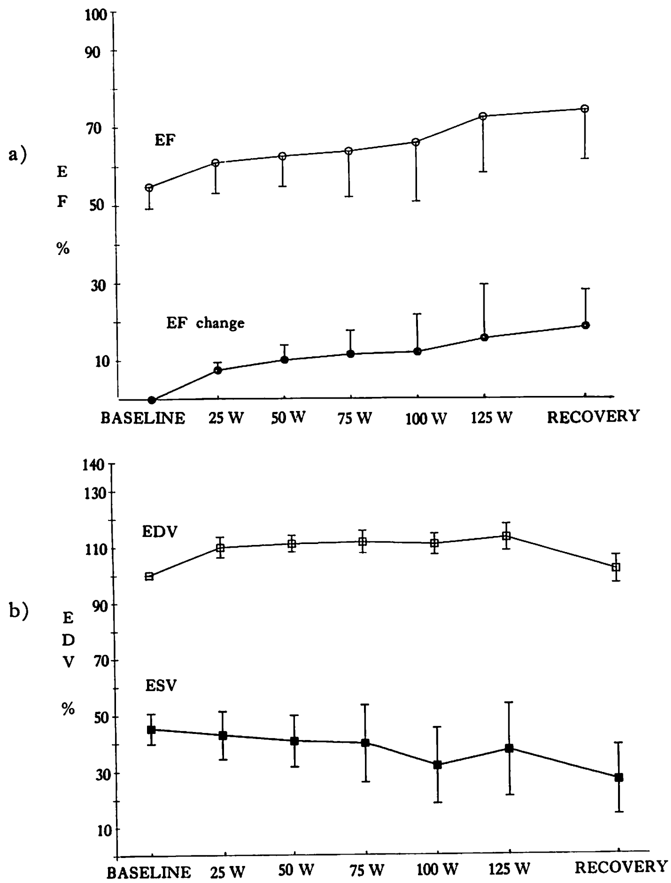

Fig. 5. Serial changes in ejection fraction (a), **and end-diastolic and end-systolic volumes** (b) **during bicycle exercise.**

end-diastolic volume and marked decreases in end-systolic volumes, compared to baseline values. The bicycle exercise study showed serial increases in ejection fraction with increased stages of exercise. However, treadmill and stair climbing studies demonstrated rapid increases in ejection fraction in the early stages of exercise, and no further changes in the later stages, The pressure rate product at the peak exercise was highest in treadmill exercise (32,600) and lowest in stair climbing (24,700). At the peak, a slight increase in end-systolic volume was observed in each exercise.

Immediately after completion of exercise, a further increase in ejection fraction was observed, particularly in bicycle and treadmill exercise studies. This increase was greatest in treadmill exercise, up to 84%. End-diastolic and end systolic volumes decreased during the immediate post-exercise recovery period.

Discussion

Dynamic erect bicycle exercise by normal persons has been the subject of extensive investigations using radionuclide angiography[6,15,16] These studies suggested that increases in end-diastolic volumes and decreases in end-systolic volumes with resultant increases in stroke volumes caused increases in ejection fraction. Therefore, both the Frank-Starling mechanism

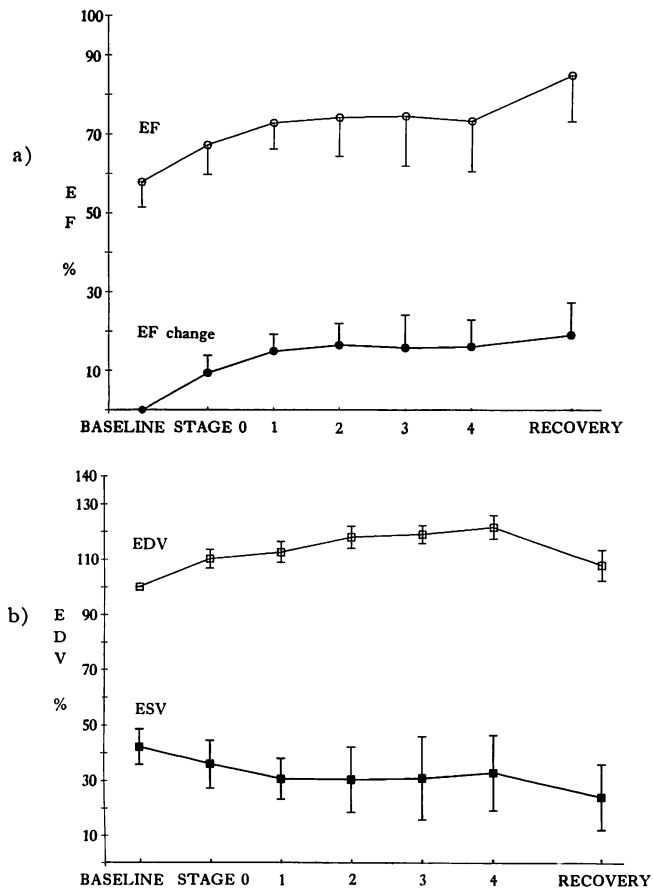

Fig. 6. Serial changes in ejection fraction (a), **and end-diastolic and end-systolic volumes** (b) **during treadmill exercise.**

and an enhanced contractile response contribute to the increase in ejection fraction with exercise.[17,18]. In the present study, similar responses were observed during treadmill exercise and climbing stairs. Continuous monitoring of left ventricular function in our study demonstrated that increases in ejection fraction occurred early, and did not change in later stages, while heart rate and systolic blood pressure steadily increased. Regardless of the type of exercise, during its peak there was a slight increase in end-systolic volume, which caused a slight decrease in ejection fraction in some patients. This is consistent with the results of previous studies showing most normal increases in stroke volume occur during the first half of a graded exercise[19,20]. At increased heart rate, there was marked shortening of diastole, limiting any further preload compensation. At the peak exercise, after anaerobic threshold, lactic acid accumulation may have an adverse impact on the myocardium[20,21]. While climbing stairs, ejection fraction and heart rate increases seemed to be more rapid; heart rate remained constant in the later stages, probably due to a constant exercise load, as compared to the graded load during bicycle and treadmill exercises.

Early in the recovery phase after exercise, decreases both in end-diastolic and end-systolic volumes were observed, resulting in further in-

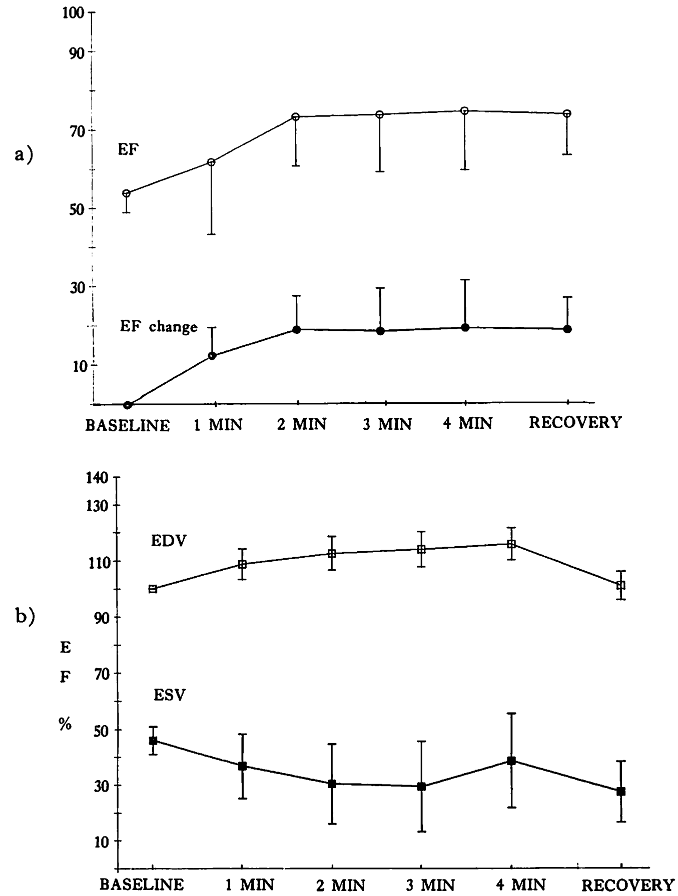

Fig. 7. Serial changes in ejection fraction (a), **and end-diastolic and end-systolic volumes** (b) **during stair climbing.**

creases in ejection fraction. Batter[22] and Plotnick[23] described a similar response during the recovery period. In the upright position, the immediate decrease in muscular pumping in the legs causes venous pooling, which can decrease left ventricular filling. In addition, an early decrease in peripheral resistance with a resultant decrease in afterload and continuing sympathetic tone allow ejection fraction to increase in this stage[23]. These phenomena were more prominent after vigorous exercise, such as treadmill or bicycle exercise.

Since Wagner et al[24] introduced a practical bedside device for repetitive measurements of left ventricular function. Several studies using the "nuclear stethoscope" showed excellent correlations between probe measurements of ejection fraction and those using gamma cameras[25,26]. Our ambulatory ventricular function monitor (VEST) extended this concept to allow continuous measurement of left ventricular function in a natural environment[10,11].

This device monitors beat-to-beat left ventricular function and ECG simultaneously to permit evaluating rapid sequential changes in cardiac function[12~14]. The time-activity curves obtained using this device can be applied to calculate ejection fraction, relative end-diastolic and end-systolic volumes, relative cardiac output, and various emptying and filling rates, all of which are valuable in assessing dynamic cardiac physiology. To reduce the effects of statistical noise and respiratory motion, 15～30 sec averaged time-activity curves were assessed in the present study.

To assure collection of adequate data using the VEST, several technical points should be checked when this instrument is being used for subjects. First, the VEST garment must be tightly fixed over the chest and its position should be confirmed by static images of the VEST and the blood pool at the beginning and the end of the study. Second, marked changes in position, such as from supine to standing, may cause cardiac rotation which can produce changes in cardiac function. The quality control steps of displaying average counts may help to identify detector motion or cardiac rotation problems, which should be eradicated before the analysis. Third, a fixed ratio (70%) of end-diastolic counts was used as a background, based on our previous data[12,13], instead of the actual background counts from a second detector, because the former data were considered more reliable. However, a significant change in background has the potential of causing large errors in calculating ejection fraction, although to a degree the main detector could also monitor such changes.

In conclusion, using the VEST, rapid and sequential changes in cardiac function are observed during a variety of exercises. This study demonstrated that ambulatory ventricular function monitoring provides a better understanding of normal cardiac physiology.

要　約

携帯用 RI 心機能モニターによる運動負荷時の心機能連続評価

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携帯用 RI 心機能モニター (VEST) は，ガンマカメラから離れた自然の環境下で，左室機能と心電図を記録できる．種々の運動負荷時の心機能を評価するため，本装置を用いて健常人 18 例に左室機能を連続的に記録した．通常の RI マルチゲート心プールスキャンの後，VEST の主検出器を左室領域に照準・固定することにより，1 心拍ごとの左室容量曲線と心電図とが記録できた．VEST 装着後，安静坐位での心機能を記録し，これをベースラインとした．その後 VEST 装着のまま，エルゴメーターによる運動負荷 (16 例)，トレッドミル負荷 (14 例)，および階段 10～16 階の歩行運動 (18 例) を行い，おのおのの心機能を連続記録した．得られた 1 心拍ごとのデータを 15～30 秒ごとに平均加算した左室容積曲線から，左室駆出率 (EF)，左室拡張末期容積 (EDV)，収縮末期容積 (ESV)，心拍数などを算出した．

運動負荷時の心機能変化では，特にトレッドミルおよび階段運動で運動早期に EDV が軽度増加，ESV が減少して EF が急激な増加を示し，運動後期には EF の増加はみられなかったのに対し，心拍数と収縮期血圧は連続的に上昇した．最大運動負荷時のダブルプロダクトは，トレッドミルで最も高く (32,600)，階段運動が最も低かった (24,700)．また運動負荷直後には EDV と ESV は急激に低下し，とりわけ負荷量の多いエルゴメーターとトレッドミル負荷で，EF はさらに増加した．

VEST は日常生活における左室機能を連続的に記録でき，種々の運動負荷時の心機能の反応を詳細に検討する上で有用な手段と考えられた．

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