Application of a Continuous Ventricular Function Monitor with Miniature Cadmium Telluride Detector to Patients with Coronary Artery Bypass Grafting

Junichi Taki, Akira Muramori, Kenichi Nakajima, Hisashi Bunko, Michio Kawasuji, Norihisa Tonami, and Kinichi Hisada

Departments of Nuclear Medicine and Surgery (I), Kanazawa University School of Medicine, Kanazawa, Japan

A continuous ventricular function monitor with a miniature cadmium telluride detector was evaluated and applied to patients with coronary bypass surgery (CABG). Ejection fraction (EF) at rest and change in EF from rest to exercise and postexercise (Y) measured with the device correlated with that of the gamma camera (X) ($Y = 0.86X + 6.8(\%)$, $r = 0.87$, $n = 110$, $p < 0.001$, and $Y = 0.96X + 0.4(\%)$, $r = 0.90$, $n = 37$, $p < 0.001$ respectively). Left ventricular function during and after supine ergometer exercise was monitored in 54 patients before and after CABG. The EF change from baseline to peak exercise improved from −5.9% ± 8.9% before CABG to 7.2% ± 7.9% after CABG ($p < 0.001$). In all patients but two, a rapid EF increase just after exercise over baseline EF was observed. This EF "overshoot" during recovery increased from 11.5% ± 6.5% to 16.4% ± 6.0% ($p < 0.001$) after CABG. The time from the cessation of exercise to EF overshoot decreased from 153 ± 80 sec to 76 ± 49 sec ($p < 0.001$) after CABG. The continuous ventricular function monitor with a miniature cadmium telluride detector is able to measure EF reliably. Following successful aortocoronary bypass, EF response during exercise improved and the EF overshoot in the recovery phase became faster and higher.

J Nucl Med 1992; 33:441–447

Gated blood-pool scintigraphy has been widely used for the noninvasive evaluation of cardiac function under conditions of rest and during exercise and pharmacological intervention. Since the time interval of data acquisition for gated blood-pool imaging requires at least 90–120 sec, continuous monitoring of changes in left ventricular function over short intervals is difficult. Recently an ambulatory ventricular function monitor (the VEST) was introduced and continuous assessment of cardiac function change during short intervals became feasible (*1–6*). Its detector consists of a sodium iodide crystal 6.5 cm in diameter with a highly sensitive parallel-hole collimator weighing 0.75 kg (*3*, *4*). Several types of small detectors have also been distributed for continuous monitoring of ventricular function (*7–10*). When a cadmium telluride (CdTe) detector is used, its small size and light weight should be beneficial for ambulatory ventricular function monitoring. We evaluated a continuous ventricular function monitor (CVM) with a lightweight miniature cadmium telluride detector and applied it to the severe coronary artery disease patients before and after coronary artery bypass grafting (CABG).

Received May 31, 1991; revision accepted Oct. 8, 1991

For reprints contact: Junichi Taki, MD, Department of Nuclear Medicine, Kanazawa University School of Medicine, 13-1 Takara-machi, Kanazawa, 920, Japan.

METHODS

Instrumentation

The system consists of CdTe probe detector, preamplifier unit, portable acquisition unit, and battery unit (Fig. 1). The CdTe detector, 16 mm in diameter and 2 mm in thickness, is equipped with a straight bore lead collimator measuring 16 mm in both diameter and length with 5 mm of wall thickness (*10*). Signals from the detector are cabled to the pulse-height analyzer and pulses greater than a 120 keV equivalent level are counted. The count rate is 25,000 cps when 3.7 MBq of a [^{99m}Tc]pertechnetate point source is placed on the surface of the collimator. The count rate is linear, up to 27,000 cps, while a 10% count loss is observed at 50,000 cps. The instrument records sequential 50-msec radionuclide count rates of the left ventricle through the detector and all the data are transferred to a laptop personal computer (LT11 NEC, Tokyo) and stored in a 3.5-in floppy disk. Timing and count information are transferred to the computer simultaneously. The detector is held in place over the left ventricle by fitting the patients with an elastic vest-like garment and attaching the detector (in plastic housing of 6 cm diameter, 4 cm height, weighing 0.4 kg) to the garment with velcro. During data acquisition, beat-to-beat left ventricular three-point smoothed time-activity curves are displayed in real time.

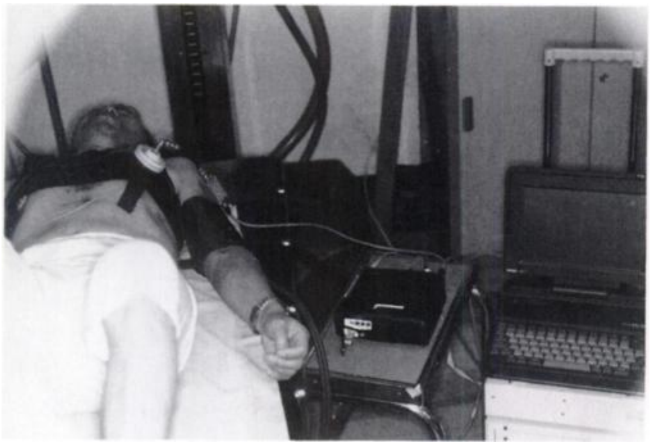

FIGURE 1. Continuous ventricular function monitor with CdTe detector. The detector is kept in place by velcro tape attached to an elastic vest-like garment worn by the subject. The portable acquisition unit, battery unit, and personal computer are also shown.

Evaluation of the Instrument

Phantom Study. Isoresponse curves were measured using a point source of [^{99m}Tc]pertechnetate. To confirm the relation between count rate and ventricular volume, 50–400 ml balloons, containing 220 KBq/ml of [^{99m}Tc]pertechnetate, were placed in water containing 15 KBq/ml of ^{99m}Tc with a distance of 4–12 cm from the collimator surface to the center of the balloons. Ventricular phantoms count rates were measured and plotted as a function of balloon volume at different distances.

Patient Studies. Comparison of ejection fraction (EF) measured by the CdTe continuous ventricular function monitor with the EF from gamma camera was made using 110 resting 90-sec gated blood-pool studies and 4–5-min CVM study performed in 61 patients with ischemic heart disease, 1 patient with dilated cardiomyopathy, and 1 with mitral regurgitation (50 men and 13 women, mean age 57 ± 8 yr). Fifty-three of the 63 patients were the same patients included in the "clinical study." In 10 patients with ischemic heart disease, gated blood-pool scintigraphy was also performed during the last 90 sec of each 2-min exercise stage and 1–3 min postexercise. Changes in EF from rest to each exercise stage and to early recovery after exercise was compared with that measured with CVM study performed 40–60 min after the exercise gated blood-pool study.

ECG gated blood-pool data were obtained for 24 frames per cardiac cycle in the left anterior oblique position with a 35-degree caudal tilt using a slant-hole collimator (Ohio Nuclear VIP-450). LVEF was analyzed using a program with a variable region of interest using a thresholding method (QMICA).

In the CVM study, EF was calculated from the stroke counts divided by background-corrected end-diastolic counts of each beat and averaged over 20 sec. Background corrections of 75%, 70%, 65%, and 60% of end-diastolic counts were performed. The EFs calculated from each background collection were compared with EFs measured by a gamma camera.

In eight patients with coronary artery disease, including five anterior and one inferior infarction (6 men and 2 women, aged 58 ± 7 yr), changes in EF due to a positioning error were confirmed by recording each 2-min set data when the detector was shifted up, right, down, and left 1 and 2 cm, respectively.

Clinical Study

Patients. Fifty-four patients with ischemic heart disease who were scheduled for CABG were recruited for the exercise study using the CVM. However, one woman was excluded from this study because of detector shift during exercise. Three patients had single-vessel coronary artery disease, 17 had double-vessel disease, and 33 had triple-vessel disease, defined as narrowing of the luminal diameter by more than 70% on coronary angiography. Twenty-nine patients had prior myocardial infarction. All patients received nitrates and calcium channel blockers. In addition to these medications, beta blockers were used in eight patients. No patient's medication was changed before or after CABG.

Gated Blood-Pool Scintigraphy and Detector Positioning. Before CABG and 4 wk after CABG, supine ergometer exercise using the CVM was performed. Each patient continued their usual medication during the exercise radionuclide study. Fifteen minutes after intravenous injection of stannous pyrophosphate, 740–925 MBq (20–25 mCi) of [^{99m}Tc]pertechnetate were injected. A 90-sec equilibrium ECG gated blood-pool scintigram was recorded at rest. At the completion of gated blood-pool scintigraphy, electrocardiographic electrodes were attached to record modified V_5, and the elastic garment was fitted around the patient's chest. With the patient in the supine position, the detector was placed over the left ventricular blood pool under gamma camera control in the left anterior oblique position. To verify adequacy of the detector's position, a 20–30-sec static image was acquired before and after the CVM study.

Supine Graded Bicycle Ergometer Exercise Under CVM Monitoring. After 4–5 min of rest, supine bicycle ergometer exercise was started with a workload of 25 W and increased by 25 W for every 2 min of stress. Exercise was terminated when either severe chest pain, ischemic ST segment depression with more than 0.2 mV, serious arrhythmia, and or fatigue occurred. At least 7 min after termination of exercise, data were recorded. Blood pressure was measured at 1-min intervals during the test.

CVM Data Analysis. Prior to data analysis, a trend plot for left ventricular counts over time was displayed to identify significant detector motion, which was represented as a sudden deviation of the plot. A decay-corrected left ventricular time-activity curve was smoothed by digital filtering, after which corresponding peak and valley counts were determined as end-diastolic and end-systolic counts, respectively. EF was calculated from the stroke counts divided by background-corrected end-diastolic counts of each beat and averaged every 20 sec. A background correction of 70% end-diastolic counts was used, based on the result of the EF comparison between the camera and CVM. Relative end-diastolic volume was considered to be 100% at the beginning of the study and subsequently expressed relative to this value. Relative cardiac output was calculated as relative stroke volume multiplied by heart rate. Correction for physical ^{99m}Tc decay was done in all patients. Biological decay correction was not performed because it varied among patients and the monitoring interval was relatively short (25–30 min at most).

EF response patterns during exercise were classified into four types (Fig. 2). In type 1, EF increased more than a 5% point from resting EF until end of exercise. Type 2 showed that EF increased more than 5% points initially, but also that EF increases could not be maintained until the end of exercise and decreased. In type 3, EF did not change significantly (within ± 5% point of resting EF). Type 4 revealed continuous EF decreases of more

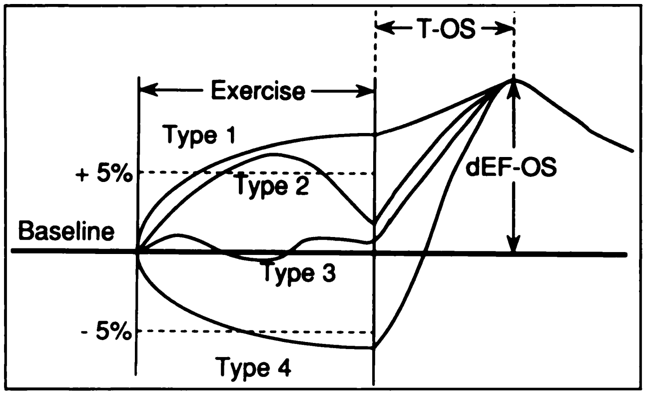

FIGURE 2. EF response type during exercise and parameters for EF overshoot during recovery. T-OS = time period from the cessation of exercise to peak EF during recovery after exercise. dEF-OS=EF change from baseline to peak EF during recovery. See text for further details.

than 5% points until end of exercise. The rapid EF increase over peak exercise EF and above the pre-exercise baseline EF during recovery was defined as EF overshoot. In addition to EF change from rest to peak exercise (dEF-Ex), the time period from the termination of exercise to peak EF overshoot during recovery (T-OS) and the change of EF from rest to EF overshoot (dEF-OS) were evaluated (Fig. 2).

Statistical Analysis

Results were described as a mean ± 1 s.d. Student's t-test was used to compare the mean value of each parameter. Paired t-tests were used to compare EF changes by detector shift. A p value of <0.05 was considered statistically significant.

RESULTS

Basic Study of the Instrumentation

Phantom Study. The isoresponse curves are shown in Figure 3. The relative isosensitivity response contours were displayed when the count rate of a point source of ^{99m}Tc was placed in the center of the collimator surface and expressed as 100%. A 10% isoresponse curve showed 5.2 cm in maximum depth and 4.1 cm in maximum width; a 5% isoresponse curve showed 8.2 cm and 5.8 cm. Figure 4 shows the correlation between balloon volume and count rate. The balloon count rate was underestimated when volume was over 200 ml with a 6 cm distance from the collimator surface to the center of the balloon. With 8–12 cm distances, however, there was no underestimation of count rate until balloon volume was 400 ml.

Patient Study. When 75%, 70%, 65%, and 60% of end-diastolic counts were used as background, the regression lines between camera EF (X) and probe EF (Y) were as follows: Y = 1.04X + 8.2, Y = 0.86X + 6.8, Y = 0.74X + 5.8, and Y = 0.65X + 5.1(%), r = 0.87 in all cases. The regression line between camera EF and probe EF was closest to the line Y = X, when 70% background correction of end-diastolic count was performed. Therefore 70% of the end-diastolic count was used as background correction in the clinical study. The correlation between gamma camera EF (X) and probe EF (Y) at rest was excellent: Y = 0.86X + 6.8(%), r = 0.87, n = 110, s.e.e. = 6.0, $p < 0.001$ (Fig. 5). EF changes from rest to exercise and post-exercise measured by the gamma camera (X) and CVM (Y) also revealed good correlation: Y = 0.96X + 0.3(%), r = 0.90, n = 37, s.e.e., = 3.5, $p < 0.001$ (Fig. 6). Each matched exercise and postexercise stage showed similar ECG change, symptom, heart rate (disparity less than 10/min) and systolic blood pressure (disparity less than 10 mmHg).

EF change by positioning error is tabulated in Table 1.

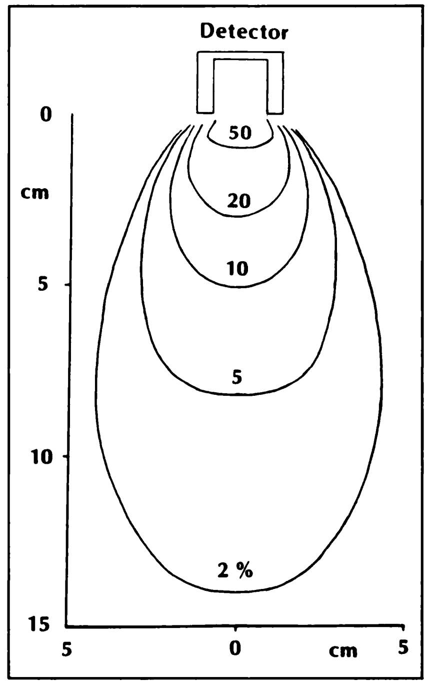

FIGURE 3. Isoresponse curves of the cadmium telluride detector in air.

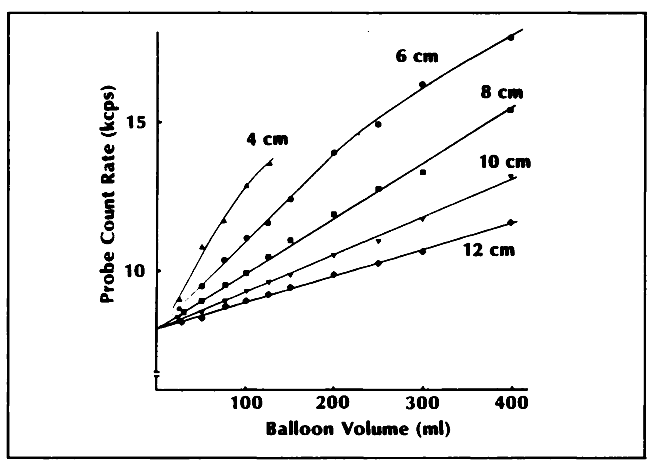

FIGURE 4. The relationship between balloon volume and probe count rate in water with background, in various distance from the probe to the center of the balloon. The count rate of the balloon was underestimated when volume was over 200 ml with 6 cm distance from collimator surface to the center of the balloon. However, with 8–12 cm distances there was no underestimation until 400 ml.

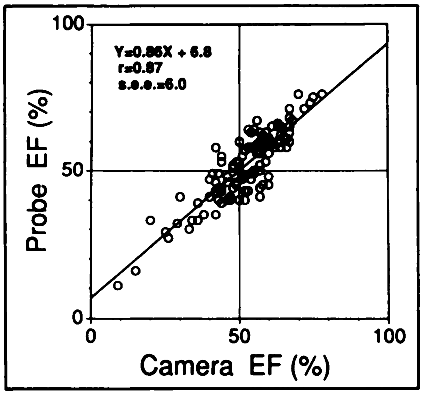

FIGURE 5. The correlation between gamma camera EF (X) and probe EF (Y) at rest.

Significant underestimation of EF was observed by upward shift of the detector, while, a 1-cm upward shift of the detector showed ≤5% EF change in all cases. Underestimation of EF (−6.1% ± 3.9%) was more significant when upward shift of the detector was 2 cm.

Clinical Study of Patients with Coronary Artery Disease

Cardiac Function Before CABG. Five patients showed type 1 EF response pattern, 6 showed type 2, 18 demonstrated type 3, and 24 patients revealed type 4, including 4, 2, 12, and 11 patients with previous myocardial infarction respectively. Just after exercise, 51 of 53 patients showed an overshoot of EF. Hemodynamic and cardiac function data for each EF response type groups are shown in Table 2. Heart rate (HR) and systolic blood pressure (BP) at peak exercise were lower in type 3 patients compared with types 2 and 4. Type 1 patients showed the highest dEF-Ex and dEF-OS with the shortest T-OS. On the other hand, type 4 demonstrated the lowest dEF-Ex and dEF-OS with the longest T-OS. Types 2 and 3 revealed intermediate values between types 1 and 4. During EF overshoot at recovery, relative end-diastolic volume (EDV) approached baseline and relative end-systolic volume (ESV) decreased significantly resulting in EF increase.

Cardiac Function After CABG. The average number of CABGs placed for one patient were 2.7. All five patients who showed type 1 EF response preserved their EF response pattern after CABG. In all six patients with type 2 EF response, EF response improved to type 1 after CABG. Thirteen of 18 patients with type 3 showed type 1 EF response after CABG and 2 patients showed types 2 and 3. After CABG, 7 of 24 patients with type 4 EF reaction before CABG demonstrated type 1 EF response, 8 showed type 2, 7 demonstrated type 3 and 2 had type 4 (Fig. 7). Cardiac function parameters before and after CABG in all patients are tabulated in Table 3. HR at peak exercise increased slightly after CABG. At peak exercise dEF-Ex increased significantly due to significant decrease in rela-

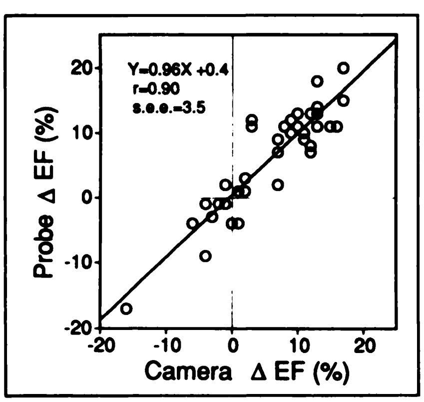

FIGURE 6. The correlation between the change of EF from rest to exercise and postexercise (ΔEF) measured by gamma camera (X) and by the probe (Y).

TABLE 1
Errors in EF Measurement by Detector Shifts

Direction of detector shift	EF change (%)	p
Upward		
1 cm	−3.0 ± 2.1	<0.01
2 cm	−6.1 ± 3.9	<0.005
Rightward		
1 cm	−0.3 ± 1.4	ns
2 cm	−0.6 ± 2.5	ns
Downward		
1 cm	0.9 ± 3.4	ns
2 cm	0.5 ± 3.8	ns
Leftward		
1 cm	0.3 ± 2.4	ns
2 cm	−2.8 ± 3.9	ns

TABLE 2
Hemodynamic and Cardiac Function Parameters in Each EF Response Type Before Bypass Grafting

	EF Response type			
	1	2	3	4
Work load (W)	63 ± 17	88 ± 21	71 ± 23	72 ± 23
HR at Ex (/min)	101 ± 21	117 ± 16*	94 ± 15	111 ± 15*
BP at Ex (mmHg)	158 ± 29	169 ± 28*	141 ± 17	162 ± 26*
Rest EF (%)	45 ± 11	55 ± 7	52 ± 12	53 ± 10
dEF-Ex (%)	8.2 ± 2.6*	−6.2 ± 5.3†	−0.1 ± 3.1	−13 ± 6.3‡
%EDV at Ex (%)	111 ± 8.8	109 ± 3.7	107 ± 5.8	106 ± 5.5
%ESV at Ex (%)	92 ± 6.2*	124 ± 15	106 ± 11†	137 ± 23
HR at OS (/min)	78 ± 16	81 ± 13	73 ± 12	79 ± 11
BP at OS (mmHg)	132 ± 19	145 ± 21	131 ± 20	139 ± 21
dEF-OS (%)	19.8 ± 7.4*	14.7 ± 7.9	11.9 ± 3.6†	8.8 ± 6.0
%EDV at OS (%)	104 ± 4.6	101 ± 4.5	103 ± 4.9*	100 ± 3.2*
%ESV at OS (%)	61 ± 25*	66 ± 17	76 ± 14	80 ± 16*
Time to OS (sec)	64 ± 17*	150 ± 42	129 ± 65†	190 ± 85

HR = heart rate; BP = blood pressure; Ex = exercise; EF = ejection fraction; EDV = end-diastolic volume; ESV = end systolic volume; CO = cardiac output; OS = EF overshoot during recovery; dEF-Ex = change of EF from baseline to peak Ex; and dEF-OS = change of EF from baseline to OS.

HR at Ex: * = $p < 0.01$; type 2 and 4 vs. 3. BP at Ex: * = $p < 0.01$; type 2 and 4 vs. 3. dEF-Ex: * = $p < 0.01$; type 1 vs. 2, 3 and 4, † = $p < 0.05$; type 2 vs. 3 and 4, ‡ = $p < 0.01$; type 3 vs. 4. %ESV at Ex: * = $p < 0.01$; type 1 vs. 2, 3 and 4, † = $p < 0.01$; type 3 vs. 2 and 4. dEF-OS: * = $p < 0.01$; type 1 vs. 4, † = $p < 0.05$; type 3 vs. 4. %EDV at OS: * = $p < 0.01$; type 3 vs. 4. %ESV at OS: * = $p < 0.05$; type 1 vs. 4. Time to OS: * = $p < 0.01$; type 1 vs. 2, 3 and 4, † = $p < 0.05$; type 3 vs. 4.

Type	Pre CABG 1	2	3	4	
Post CABG 1	5	6	13	7	31
2			2	8	10
3			3	7	10
4				2	2
	5	6	18	24	

FIGURE 7. Change in EF type during exercise from pre-bypass to post-bypass surgery.

tive ESV and similar relative EDV after CABG. During recovery EF overshoot occurred earlier (from 153 ± 80 to 76 ± 49 sec, $p < 0.001$) and dEF-OS increased from 11.5 ± 6.5 to 16.4 ± 6.0% ($p < 0.001$) after CABG. The change of cardiac function parameters after CABG in each preoperative EF response type group are shown in Table 4. HR and BP increased after CABG but significantly in only the HR of type 3 patients. In the type 1 group, dEF-Ex, dEF-OS and T-OS did not change significantly. In type 2, dEF-Ex increased and T-OS decreased after CABG. In types 3 and 4, dEF-Ex and dEF-OS increased and T-OS became shorter significantly after bypass surgery. Although after CABG, type 4 patients still showed relatively less dEF-Ex and longer T-OS, dEF-OS increased to similar values of other types.

DISCUSSION

An ambulatory ventricular function monitor (VEST), described by Strauss and associates as a wearable instrument with small radionuclide detectors (*1*), is an extension of the nuclear stethoscope (*11*). The VEST and this CVM with a Cd-Te detector provides a continuous beat-by-beat recording of left ventricular function and should be useful in the evaluation of cardiac dysfunction during exercise and pharmacological intervention, mental stress, and daily living. Such information may be helpful in the evaluation and treatment of patients with ischemic heart disease because this type of information may not be obtained by formal treadmill studies. Also, it may be helpful in defining appropriate exercise limits for patients and providing prognostic evaluation for future coronary disease events (*4*). Although a CVM cannot provide information about regional wall motion, even in a formal stress test, a more precise analysis of the global cardiac response during stress and recovery is possible.

TABLE 3
Hemodynamic and Cardiac Function Parameters Before and After Bypass Surgery

	Pre-CABG	Post-CABG	p
Work load (W)	73 ± 22	73 ± 22	ns
HR at peak Ex (/min)	105 ± 18	114 ± 17	<0.01
BP at peak Ex (mmHg)	155 ± 26	162 ± 26	ns
Rest EF (%)	51.9 ± 10.5	53.9 ± 10.6	ns
dEF-Ex (%)	−5.9 ± 8.9	7.15 ± 7.9	<0.001
%EDV at Ex	107 ± 5.8	105 ± 5.0	ns
%ESV at Ex	121 ± 24	85 ± 21	<0.001
HR at OS (/min)	77 ± 12	95 ± 14	<0.001
BP at OS (mmHg)	137 ± 20	135 ± 21	ns
dEF-OS (%)	11.5 ± 6.5	16.4 ± 6.0	<0.001
%EDV at OS (%)	102 ± 4.3	102 ± 3.9	ns
%ESV at OS (%)	75 ± 17	64 ± 19	<0.005
Time to OS (sec)	153 ± 80	76 ± 49	<0.001

See Table 2 for abbreviations.

TABLE 4
Hemodynamic and Cardiac Function Parameters After Bypass Grafting in each Preoperative EF Response Type

	Preoperative EF response type 1	2	3	4
Work load (W)	68 ± 16	88 ± 21	70 ± 25	73 ± 19
HR at Ex (/min)	111 ± 19	114 ± 13	108§ ± 18*	119 ± 17*
BP at Ex (mmHg)	170 ± 32	160 ± 22	151 ± 22*	170 ± 27*
Rest EF (%)	50 ± 16	56 ± 12	55 ± 12	54 ± 9
dEF-Ex (%)	11.4 ± 3.0**	12.5† ± 5.9*	9.4† ± 7.8*	3.3† ± 7.6
%EDV at Ex (%)	105 ± 7.2	108 ± 3.8	105 ± 5.1	104 ± 4.8
%ESV at Ex (%)	75 ± 19	73† ± 19*	80† ± 20*	94† ± 19
HR at OS (/min)	96 ± 17	93 ± 11	94† ± 18	96† ± 12
BP at OS (mmHg)	145 ± 21	126 ± 18	135 ± 20	135 ± 23
dEF-OS (%)	17.8 ± 3.5	21.7 ± 8.3*	15.9§ ± 5.9	15.3† ± 5.4*
%EDV at OS (%)	103 ± 5.8	103 ± 2.5	104 ± 4.2*	101 ± 3.4*
%ESV at OS (%)	57 ± 23	50 ± 23*	64§ ± 19	69§ ± 17*
Time to OS (sec)	42 ± 23**	80§ ± 57	57† ± 41**	96† ± 48

See Table 2 for abbreviations.
§ $p < 0.05$ compared with pre-CABG.
† $p < 0.01$ compared with pre-CABG.
HR at Ex and BP at Ex: * = $p < 0.05$; type 3 vs. 4. dEF-Ex: ** = $p < 0.01$; type 1 vs. 4, * = $p < 0.05$; type 2 and 3 vs. 4. %ESV at Ex: * = $p < 0.05$; types 2 and 3 vs. 4. dEF-OS: * = $p < 0.05$; type 2 vs. 4. %EDV at OS: * = $p < 0.05$; type 3 vs. 4. %ESV at OS: * = $p < 0.05$; type 2 vs. 4. Time to OS: ** = $p < 0.01$; type 1 and 3 vs. 4.

CdTe Detector

A CVM should satisfy several conditions. First, it must be light and compact for easy and stable connection to the patient's chest and not hamper patient mobility. Second, it should offer high sensitivity and high temporal resolution time-activity curve data from the left ventricular blood pool. Third, for ambulatory use, the data collection system should be off line. Although data collection is online in this miniature Cd-Te probe system (from the probe to the personal computer for data transfer at this stage), it satisfies the first two requirements described above.

The previously described VEST system (Capintec Inc, Ramsey, NJ) uses a 6.5 cm diameter NaI crystal with a high sensitivity parallel-hole collimator, providing similar data to that obtained from a circular region of interest with a gamma camera image. On the other hand, since a

Cd-Te detector uses a straight-bore collimator, its count efficiency is dependent on the distance from detector to the target (e.g., nuclear stethoscopes). Consequently, the counts from the deeper part of the left ventricle may be underestimated compared to those with the VEST detector. This potential pitfall should be considered, especially when the left ventricle is large. In addition, a severely dilated ventricle could not be covered entirely by the field of view of the detector. A phantom study showed underestimation of the balloon count over 200 ml when the distance between the center of the balloon and the surface of collimator was 6 cm. This phenomenon was considered to be due to the relatively small field of view near the collimator, resulting in count loss from the partially uncovered balloon area by detector's field of view. When the distance from the collimator surface to the center of the balloon was 8–12 cm, linearity between phantom volume and recorded counts was kept to 400 ml of balloon volume. In spite of these potential pitfalls, clinical data revealed sufficient EF correlation with gamma camera EF in the resting condition and in the EF change from rest to exercise and postexercise to be clinically useful.

The smaller and lighter weight CdTe detector rather than NaI detector may have a potential advantage in terms of application for longer ambulatory data acquisition and for female patients.

For background correction, we used 70% of the end-diastolic counts because it offered the best correlation between probe EF and camera EF. Ideally, a similar background correlation method used in the camera EF calculation is desirable. Although we tried to use the same CdTe detector for background correction adjacent to the left side of the left ventricle, space for another detector was limited, especially in small patients, and sometimes the background detector was dislodged by movement of the left arm, resulting in unstable count data. A more compact background detector combined with the main detector system should be tried in the future.

To measure ejection fraction, accurate detector positioning is important. An upward shift of 2 cm of the detector resulted in a significant EF decrease, probably due to atrial count contamination. Minimal EF change was observed when the detector shifted in other directions. As a result, the detector should be positioned carefully so as not to include atrial activity. Other factors that may influence the stability of EF calculations may be respiratory movement of the heart, especially in vigorous exercise. But this effect of EF measurement also occurs in gated blood-pool scintigraphy, in which patient movement against the gamma camera can also occur. On the other hand in the CVM study, the detector is attached to the thorax (*1*).

EF Response Pattern During Exercise

Four different types of EF response during exercise were observed. Conventional radionuclide ventriculographic stress studies in normal subjects revealed substantial increases in EF due to increasing EDV and decreasing ESV with vigorous exercise (*12*, *13*). Type 1 EF response showed a mild increase of EDV and a significant decrease of ESV during exercise, resulting in a rise in EF considered to be a normal EF response pattern. On the other hand, for type 4 EF response, continuous decrease in EF during exercise with mild EDV increase and significant ESV increase was considered absolutely abnormal. Type 3, however, was considered to be an abnormal EF response because there was no EF increase even at a low work load. However, in a functional manner type 3 might be better than type 4 since significant EF decrease was not observed until peak exercise. Type 2 EF response demonstrated initial increase in EF followed by a decrease in EF with increased work load. This type of EF reaction can occur in normals. Using stress gated blood-pool scintigraphy, Slutsky, et al. found that four of ten normal subjects demonstrated maximum EF prior to peak exercise (*14*). Flamm et al. disclosed that 14 normal volunteers showed maximum EF increase at 50% of maximum work load and gradual EF decrease with an increasing work load using the VEST (*15*). Since in both studies EF at peak exercise was maintained above baseline, type 2 EF reaction, preserving EF above baseline at peak exercise, may be a normal reaction. Two of six type 2 patients showed EF above baseline at peak work load before CABG.

Change in EF Response Pattern After CABG

Before CABG, 24 patients (45%) showed type 4 EF response and 18 (34%) showed type 3, whereas after CABG only 2 demonstrated type 4 and 10 showed type 3 EF response, indicating improvement of cardiac function during exercise as a result of increasing coronary blood supply by bypassed vessels (*16*, *17*). After CABG, 10 patients demonstrated type 2 EF response, but only 2 showed a lower EF than baseline at peak exercise. Although 12 patients revealed occlusion of one of the bypassed vessels, only 1 demonstrated the same pre-bypass EF response pattern (type 4).

Ventricular septal motion abnormality frequently occurs after CABG and it may affect EF measurement. This phenomenon is thought to be related to sternotomy and pericardiotomy rather than septal ischemia or perioperative infarction and no deterioration of septal systolic thickening was observed (*18*, *19*). It is unlikely that EF measurements at rest and during exercise are significantly influenced by septal motion abnormalities in that the detector completely covers the left ventricle during the cardiac cycle, because the CdTe detector measures global left ventricular function not regional EF.

EF Overshoot After Exercise

EF change during the recovery period after exercise is obtained easily using this device. Before CABG, all the patients except two demonstrated rapid EF increase above baseline EF just after the cessation of exercise. This EF elevation was caused by the approach of EDV to baseline and a significant transient reduction of ESV, resulting in increased stroke volume.

This finding was consistent with that of Cumming who noted that the highest stroke volume occurred during the first 2 min of recovery from supine exercise by the dye dilution method in normal subjects (*20*), and is also compatible with that of Flamm et al., who revealed that the EDV rapidly approached baseline and the ESV reached a minimum value 2–4 min after peak exercise in normal volunteers using the VEST (*14*). In patients with coronary artery disease, other investigators also observed an EF increase during early recovery after exercise (*21–23*). Our data showed that high EF increase from baseline to peak exercise was followed by high and rapid EF overshoot during early recovery, and poor EF response to exercise was followed by a small and delayed EF overshoot during recovery. After revascularization, EF at peak exercise increased and EF overshoot became faster and higher. These findings indicated that the more delayed and lower EF overshoot during early recovery implied more severe exercise-induced ventricular dysfunction by ischemia. Schneider et al. revealed that patients with delayed recovery of ventricular dysfunction after exercise demonstrated more severe coronary artery disease (*22*). The mechanism of EF overshoot during recovery may be due to the following factors: (1) decrease in venous return due to the decline of muscular venous pumping makes EDV return to baseline; (2) the reduction of afterload and blood pressure may be due to decreasing peripheral vascular resistance; and (3) increased myocardial contractility by continuing catecholamine stimulation. Decrease of afterload in the setting of some augmentation of contractility could allow ESV to decrease and EF to increase during early in recovery. One could postulate that the recovery from ischemia is retarded and the recovery of myocardial contractility is delayed, resulting in slow and low EF overshoot.

CONCLUSION

The continuous ventricular function monitor with a miniature Cd-Te detector permits reliable EF measurement during rest, exercise and recovery, providing additional dynamic pathophysiological cardiac function response to exercise. The patients with more severely decreased EF during exercise demonstrated greater delayed and smaller EF overshoot during recovery. After bypass surgery EF response during exercise improved and EF overshoot during recovery became more rapid and higher.

REFERENCES

1. Strauss HW, Lazewatsky J, Moore RH, et al. The VEST: a device for the continuous monitoring of cardiac function in ambulatory patients [abstract] *Circulation* 1979;59:II-246.
2. Wilson RA, Sullivan PJ, Moore RH, et al. Ambulatory ventricular function monitor: validation and preliminary clinical results. *Am J Cardiol* 1983;52:601–606.
3. Tamaki N, Gill JB, Moore RH, Yasuda T, Boucher CA, Strauss HW. Cardiac response to daily activities and exercise in normal subjects assessed by an ambulatory ventricular function monitor. *Am J Cardiol* 1987;59:1164–1169.
4. Kayden DS, Wackers FJTh, Zaret BL. Silent left ventricular dysfunction during routine activity after thrombolytic therapy for acute myocardial infarction. *J Am Coll Cardiol* 1990;15:1500–1507.
5. Taki J, Yasuda T, Tamaki N, et al. Temporal relation between left ventricular dysfunction and chest pain in coronary artery disease during activities of daily living. *Am J Cardiol* 1990;66:1455–1458.
6. Breisblatt WM, Weiland FL, McLain JR, Tomlinson GC, Burns MJ, Spaccavento LJ. Usefulness of ambulatory radionuclide monitoring of left ventricular function early after acute myocardial infarction for predicting residual myocardial ischemia. *Am J Cardiol* 1988;62:1005–1010.
7. Hoffer PB, Berger HJ, Steidley J, Brandel AF, Gottschalk A, Zaret B. A miniature cadmium telluride detector module for continuous monitoring of left ventricular function. *Radiology* 1981;138:477–481.
8. Harrison KS, Liu X, Han S, Camargo EE, Wagner HN. Evaluation of a miniature CdTe detector for monitoring left ventricular function. *Eur J Nucl Med* 1982;7:204–206.
9. Broadhurst P, Cashman P, Crawley J, Raftery E, Lahiri A. Clinical validation of a miniature nuclear probe system for continuous on-line monitoring of cardiac function and ST-segment. *J Nucl Med* 1991;32:37–43.
10. Suzuki Y, Ide M, Murakami T, et al. Radionuclide cardiac monitoring system using dual cadmium telluride (CdTe) detectors: specifications and some clinical applications. *Nucl Med Commun* 1987;8:431–439.
11. Wagner HJ Jr, Wake R, Nickoloff E, Natarajan TK. The nuclear stethoscope: a simple device for the generation of left ventricular volume curves. *Am J Cardiol* 1976;38:747–750.
12. Poliner LR, Dehmer GJ, Lewis SE, Parkey RW, Blomqvist CG, Willerson JT. Left ventricular performance in normal subjects: a comparison of the responses to exercise in the upright and supine positions. *Circulation* 1980;62:528–534.
13. Iskandrian AS, Hakki A, Kane SA, Segal BL. Quantitative radionuclide angiography in assessment of hemodynamic change during upright exercise: observations in normal subjects, patients with coronary artery disease and patients with aortic regurgitation. *Am J Cardiol* 1981;48:239–246.
14. Slutsky R, Karliner J, Ricci D, et al. Response of left ventricular volume to exercise in man assessed by radionuclide equilibrium angiography. *Circulation* 1979;60:565–571.
15. Flamm SD, Taki J, Moore BS, et al. Redistribution of regional and organ blood volume and effect on cardiac function in relation to upright exercise intensity in healthy human subjects. *Circulation* 1990;81:1550–1559.
16. Kent KM, Borer JS, Green MV, et al. Effects of coronary artery bypass on global and regional left ventricular function during exercise. *N Engl J Med* 1978;298:1434–1439.
17. Brundage BH, Massile BM, Botvinick EH. Improved regional ventricular function after successful surgical revascularization. *J Am Coll Cardiol* 1984;3:902–908.
18. Lindsay JJr, Nolan NG, Kotlyarov EV, Goldstein SA, Bacos JM. Radionuclide evaluation of the interventricular septum following coronary artery bypass surgery. *Radiology* 1982;142:489–493.
19. Schnittger I, Keren A, Yock PG, et al. Timing of abnormal interventricular septal motion after cardiopulmonary bypass operations. J Thorac Cardiovasc Surg 1986;91:619–623.
20. Cumming GR. Stroke volume during recovery from supine bicycle exercise. *J Appl Physiol* 1972;32:575–578.
21. Plotnik GD, Becker LC, Fisher ML. Changes in left ventricular function during recovery from upright bicycle exercise in normal persons and patients with coronary artery disease. *Am J Cardiol* 1986;58:247–251.
22. Schneider RM, Weintraub WS, Klein LW, Seelaus PA, Agarwal JB, Helfant RH. Rate of left ventricular functional recovery by radionuclide angiography after exercise in coronary artery disease. *Am J Cardiol* 1986;57:927–932.
23. Dymond DS, Foster C, Grenier RP, Carpenter J, Schmidt DH. Peak exercise and immediate postexercise imaging for the detection of left ventricular functional abnormalities in coronary artery disease. *Am J Cardiol* 1984;53:1532–1537.