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TECHNICAL NOTES

Measurement of Left Ventricular Function During Arm Ergometry Using the VEST™ Nuclear Probe

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Abstract/Résumé

A chest-mounted left ventricular (LV) nuclear probe (VEST™) for use during arm and leg ergometry is presented, with a discussion of the validity and reproducibility of LV function measures at rest and exercise. During both arm and leg ergometry in trained subjects, transient changes in LV function/volumes were observed. LV ejection fraction and relative end-systolic and end-diastolic volumes were 25 to 30% less with the arms versus the legs, agreeing with data from other studies using conventional techniques. At peak exercise with both limbs, LV ejection fraction and relative LV end-systolic volume increased, followed by immediate postexercise normalization. The effect was greatest with the arms and reflects the effect of high intramuscular and arterial pressures generated during arm cranking, leading to increased LV afterloading. The VEST™ permits rapid and noninvasive assessment of LV function during arm exercise, avoiding the limitations of other techniques.

Une sonde nucléaire du ventricule gauche de marque VEST™ ajustée contre la poitrine, est analysée du point de vue de sa validité et de la reproductibilité de ses mesures de la fonction ventriculaire au repos et au cours d'épreuves sur ergocycle pour les membres

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supérieurs et inférieurs. Au cours de ces épreuves, des variations passagères de la fonction ventriculaire sont observées chez des sujets entraînés. La fraction éjectée du ventricule gauche et les volumes relatifs télésystoliques et télédiastoliques sont de 25 à 30% inférieurs au cours du travail au moyen des membres supérieurs, conformément aux autres études faisant usage des techniques conventionnelles. Au faîte de l'effort, la fraction éjectée du ventricule gauche et le volume relatif télésystolique augmentent puis se normalisent immédiatement après l'effort. L'effet est plus marqué au cours de l'exercice au moyen des membres supérieurs: les pressions intramusculaire et artérielle sont plus élevées et il en est de même de la postcharge ventriculaire. La sonde de marque VEST™ permet une évaluation rapide et non invasive de la fonction ventriculaire au cours de l'exercice des membres supérieurs, évitant ainsi les limites reliées aux autres techniques.

Introduction

The first nuclear probes were developed for continuous monitoring of left ventricular (LV) function at the bedside (Breisblatt and Schulman, 1989; Wagner et al., 1976). Since their experimental introduction in the 1970s these probes have been further improved and miniaturized. Reliable measurements of transient LV function using these probes have been documented during a variety of physical activities including exercise testing (Breisblatt et al., 1991; Flamm et al., 1990; Tamaki et al., 1987; Yang et al., 1991b), portable LV function monitoring (Breisblatt et al., 1988b; Pfisterer et al., 1988; Tamaki et al., 1988), and positive pressure breathing (Goodman et al., 1992; 1994). Measurements of LV function under these conditions have been impractical or impossible using traditional invasive (angiography) and noninvasive techniques such as multigated radionuclide angiography (MUGA) and echocardiography. In addition, these latter techniques have not allowed for assessment of LV function during arm exercise. In this paper we outline our use of the VEST™ nuclear probe to measure LV function and diastolic filling during upper-extremity ergometry in normal subjects.

NUCLEAR PROBES AND ASSESSMENT OF LV FUNCTION

Nuclear probes provide a high degree of temporal resolution, enabling extremely short acquisitions (e.g., 2 sec of beat-to-beat data vs. 120 sec with conventional radionuclide techniques). These chest-worn nuclear probes consist of a single scintillation crystal and function as one large pixel, tracking changes in left ventricular count rate through the cardiac cycle over the entire LV. The changes in count rate in LV during each ECG-gated cardiac cycle, or any number of averaged cycles, are recorded. Since an LV region of interest from a ventricular image is not obtained with this technique, nuclear probes measure only changes in relative chamber volumes (% increase or decrease from an established baseline measurement). The disadvantage with this technique is loss of spatial resolution and the inability to assess regional ventricular wall motion. However, as outlined in Table 1, the VEST™ offers acceptable reproducibility and validity during cycle exercise. In addition to relative LV volumes, the VEST™ also measures rates of LV filling and ejection. LV function may be measured for periods of up to 10 hrs, until the normal biological and physical decay of technetium–99m (^{99m}TC) limits further reliable use (Iskandrian and Heo, 1989). Because of its relatively small size and capabilities, we sought to apply this technology in assessing LV function during arm exercise.

Table 1 Summary of Exercise VEST™ vs. MUGA Validation and Reproducibility Studies

Author	Measure	Comparison	*n*	Subj.	*r*	*SEE*	95% CI	Δ
Yang et al., 1993	LVEF peak	VEST vs. MUGA	22	CAD	.93*	0.10	–	4.8 ±5.0
Yang et al., 1991a	LVEF peak	VEST 1 vs. VEST 2	9	Norm.	.90*	–	0.72, 0.90	–
	ΔLVEF peak	VEST vs. MUGA	36	Norm.	.78**	–	0.61, 0.88	–
Freeman et al., 1990	LVEF peak	VEST vs. MUGA	42	CAD	.91	3.86	–	–
	ΔLVEF peak	VEST vs. MUGA	32	CAD	.86	0.62	–	–
Yang et al., 1989	LVEF peak	VEST 1 vs. VEST 2	9	CAD	.88*	–	–	1.8 ±1.2
	LVEF all exerc. levels	VEST 1 vs. VEST 2	36	CAD	.94*	–	–	1.7 ±1.3
Breisblatt et al., 1988b	LVEF peak	VEST vs. angiography cardiac phantom	35	CAD	.90	3.20	–	–
Tamaki et al., 1988	LVEF peak	VEST vs. MUGA	43	Norm.	.86	5.75	–	–
Pfisterer et al., 1988	LVEF peak	VEST vs. MUGA	19	CAD	.98	–	–	2%
	ΔLVEF peak	VEST vs. MUGA	19	CAD	.88	–	–	2%

Note. ΔLVEF peak = change in LVEF from rest to peak exerc., MUGA = multigated radionuclide angiography; CAD = coronary artery disease patients, Δ = difference in scores ± *SD*.
*Interclass correlation; **Lin concordance effect.

Methods

DESCRIPTION AND INSTRUMENTATION

The VEST™ (Capintec, Inc., Ramsay, NJ) is a 0.7-kg parallel-hole NaI collimator 5 cm in diameter (Figure 1). The portable system weighs 3.4 kg and can be operated by battery for up to 10 hrs. The probe attaches to an adjustable sleeve on the plastic-moulded garment, which then is secured onto the chest. In the present study, positioning of the probe over the LV was accomplished with

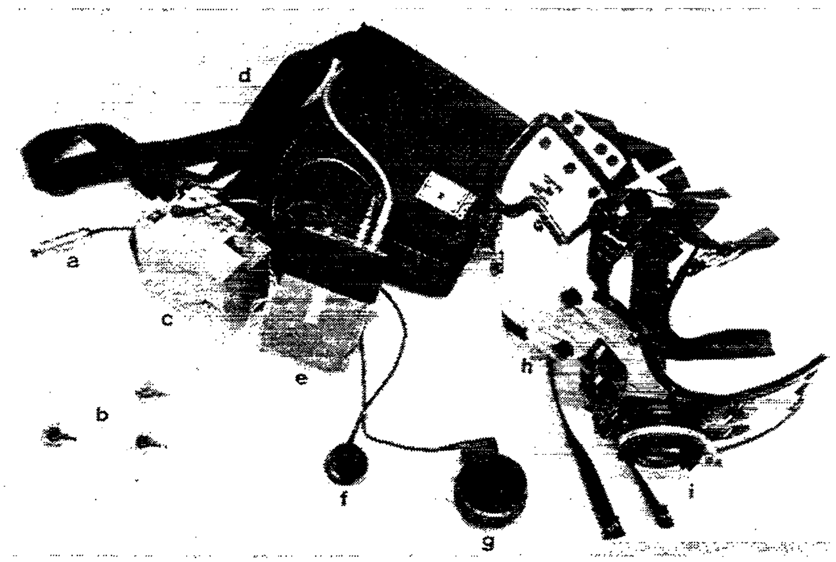

Figure 1. VEST™ hardware. (a) event marker button, (b) ECG electrodes and leads, (c) nuclear data interface module, (d) carrying bag, (e) ECG recording cassette unit, (f) small background probe, (g) left ventricular NaI probe, (h) plastic adjustable vest, (i) adjustable LV probe attachment flange.

standard MUGA that required in vivo red cell labeling of ^{99m}TC, according to standardized methods (Freeman et al., 1981; Slutsky et al., 1979, Zaret and Wackers, 1993). The shadow of the VEST™ detector was superimposed over the LV image with the subject seated. The detector's position in the plastic vest was adjusted to allow a slight caudal tilt and 40° left anterior oblique angle for optimal ventricular separation.

Background counts were estimated as 74% of resting end-diastolic counts. Estimation of background counts in this manner has been shown to produce good estimations of true background counts comparable to background levels measured over the right lung field with MUGA (Breisblatt et al., 1988a; 1988b; Tamaki et al., 1987). During all rest and exercise tests, nuclear and ECG data were continuously acquired and stored on tape in the carrying pack, which was positioned close to the subject during the tests (Figure 1).

ARM ERGOMETRY

Eight well-trained male subjects volunteered for the study, as part of a separate investigation studying limb counterpressure during arm cranking. They had signed a consent form outlining the protocol which had been approved by our institute's human ethics committee. They first completed an incremental cycle ergometry test while wearing the VEST™. The tests were performed on a Quinton™ electronically braked cycle ergometer at an intensity corresponding to 20, 30, 60, 80, and 100% of each person's peak exercise workload, as determined previously.

One hour after this leg cycle test the subjects performed arm ergometry while seated, with the rotational axis of the ergometer (Monarch Rehab Trainer) horizontal with the acromion (Figure 2). The protocol used was incremental and continuous, with the subjects cranking at 30, 60, 80, and 100% of previously determined peak levels for 2 min each. A metronome was used to maintain cranking at 60 rpm throughout the test. All subjects were able to exercise at the 100% level for at least 1 min. The experimenter pressed an event marker button connected to the VEST™ data acquisition module at each stage of exercise to time-stamp exercise workload changes for off-line editing.

During arm cranking the greatest concern was probe movement away from the LV blood pool caused by trunk rotations that accompany arm cranking. However, recent data from our laboratory have indicated that as much as a 3.2-cm lateral or vertical shift can be tolerated during monitoring before LV ejection fraction (EF) results are significantly affected (Freeman et al., 1993). The probe's position was checked before and after exercise and found to have retained its original position over the LV. Furthermore, prior to exercise we had subjects vigourously rotate the trunk to simulate excessive motion during actual arm

Figure 2. Subject during a multistage arm ergometry test wearing the VEST™ nuclear probe. Experimenter on the left is depressing the event marker button and recording for later editing; experimenter on the right is monitoring the subject's HR using a Polar wireless monitor.

cranking in order to check probe tracking and maintenance of position over the LV. This manoeuvre produced small increases in heart rate and LVEF, yet did not produce abrupt changes in count rate to indicate probe position slippage (Tamaki et al., 1987; Yang et al., 1991a). Blood pressure measurements were not performed during any exercise test.

DATA ANALYSIS

The data were downloaded from the cassette using the customized VEST™ software for off-line analysis of ECG and nuclear data with an IBM IRT computer. Initially the file was checked for proper time-activity curve recording. The period of measurement was then specified and parameters were selected for analysis. Manually recorded events and times, corresponding with depression of the event marker button, were added to the file at this point. Temporal resolution of each subject's file containing continuous beat-to-beat data was set at 30-sec averaged epochs. Data output was in tabular form for subsequent reduction and analysis, as well as in trend-plot format (Figure 3). Files were then downloaded into an Apple Macintosh IIcx computer for data reduction using spreadsheet software (Microsoft Excel) and statistical analysis (SuperAnova, Abacus Concepts, Inc.).

Available measurements included heart rate (HR; bpm), LVEF (%), LV relative end-diastolic volume (LVEDVr), relative end-systolic volume (LVESVr), relative stroke volumes (SVr), relative cardiac output (COr), peak filling rate (PFR; $+EDV \cdot s^{-1}$), peak ejection rates (PER; $-EDV \cdot s^{-1}$), time-to-peak filling rate (TPFR; ms), and first-third filling rate (FTFR; % of diastole). Since real-time data are not displayed with the VEST™, we used a Polar XL monitor to track HR during exercise (for adjustment in work rate). The HR monitor's transmitter unit was placed just below the plastic vest garment on the abdominal muscles using ECG electrodes.

Results and Discussion

A representative trend plot of HR, LVEF, LVEDVr, and LVESVr during a preliminary leg cycle test and an arm crank test is presented in Figure 3. Mean heart rate, LVEF, LVEDVr, COr, and PFR at rest, leg cycle exercise, and arm cranking are presented in Table 2. The LV responses to upright cycle ergometry in these normal subjects are consistent with findings from other laboratories: modest increases in LVEF and LVEDVr, with small increases in LVESVr until ~50% of peak exercise, followed by a plateau up to peak levels (Flamm et al., 1990; Pfisterer et al., 1988; Tamaki et al., 1987). At peak exercise there is an increase in LVESVr and a decrease in LVEF, followed by a rapid overshoot in LVEF due to a rapid decline in LVESVr immediately postexercise. This overshoot phenomenon has been observed previously using the VEST™, and is not evident using MUGA during exercise tests because of the greater time requirement for data acquisition. The LV response to arm cranking was similar to leg cycling and is in agreement with previous measurements of stroke volume during arm cranking (Clausen et al., 1970; Ng et al., 1987; Toner et al., 1990); LV volumes during arm cranking were only 60 to 80% of those observed during leg exercise. It is likely that the smaller LV volumes and LVEF during arm cranking reflect

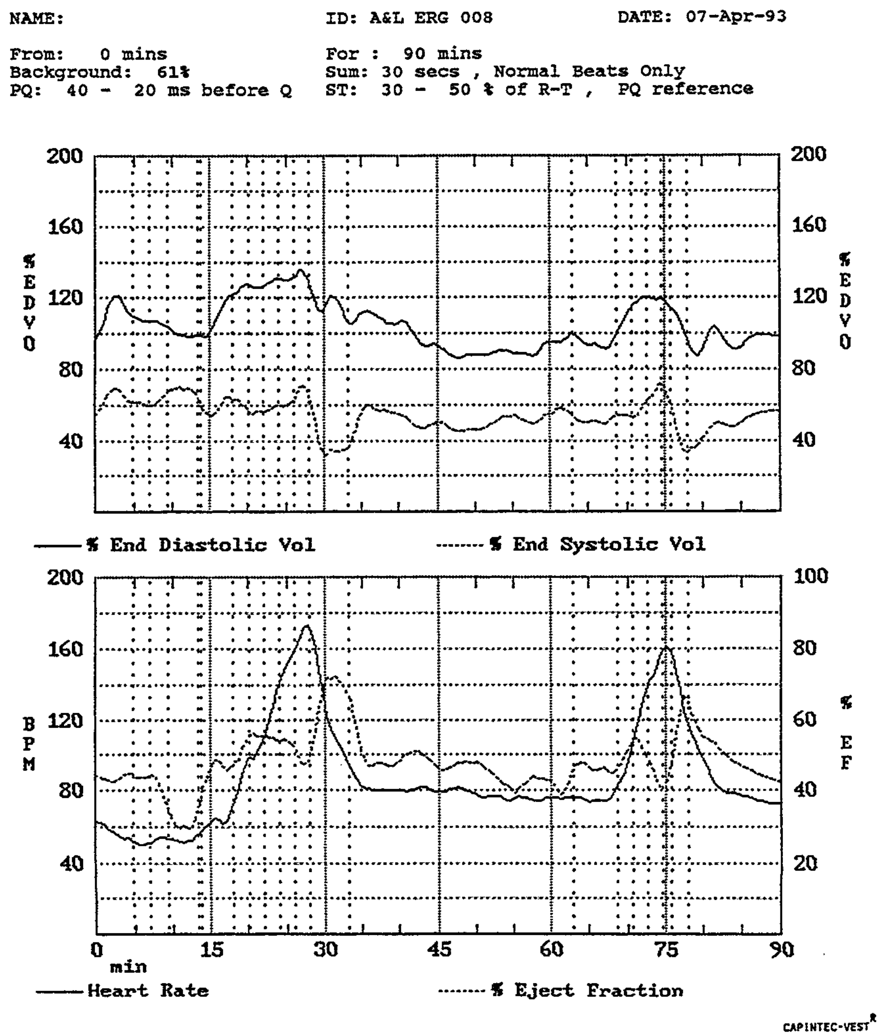

Figure 3. VEST™ trend plot during a multistage leg cycle maximal test (t = 15–30 min), a 30-min rest, and a multistage arm cranking test (t = 65–90 min). Top panel: solid lines are changes in relative LV end-diastolic vol. (%EDVO), broken lines are changes in relative LV end-systolic vol. (%ESVO). Both volumes expressed as % of resting counts. Bottom panel: solid lines are changes in heart rate (BPM), broken lines are changes in absolute LV ejection fraction (%EF).

both a diminished venous return (as measured by LVEDVr) and an increased afterload (LVESVr), especially at peak exercise when an elevation in intramuscular pressure causes a disproportionate increase in blood pressure. This is suggested by the overshoot in LVEF, corresponding to a rapid decrease in LVESVr immediately postexercise.

Table 2 LV Function Measured With Vest™ at Rest, Peak Cycle, and Peak Arm Cranking Ergometry

	HR (bpm)	VO_2peak (L·min^{-1})	LVEF (%)	LVEDVr (% cts/10 ms)	Rel. cardiac output (EDV·min^{-1})	Peak filling rate (EDV·s^{-1})
Arm						
Rest	61.1 ±5.4		49.0 ±1.6	91.0 ±2.2	28.2 ±1.8	2.2 ±0.20
Peak	152 ±5.0	2.56 ±0.16	55.9 ±2.7	97.3 ±3.7	86.6 ±4.2	5.2 ±0.25
Leg						
Rest	62.8 ±6.8		48.2 ±2.3	98.3 ±7.5	31.1 ±3.8	2.2 ±0.22
Peak	169.3 ±4.5	4.21 ±0.19	60.9 ±1.7	110.3 ±4.4	115.2 ±5.1	6.4 ±0.28

Note. Data are mean ± *SEM*. LVEF: left ventricular ejection fraction; LVEDVr: relative left ventricular end-diastolic volume.

These data suggest that measurement of LV function using the VEST™ during arm cranking is feasible. This is in contrast to MUGA, which is impractical due to the large gamma camera size and prerequisite 2-min steady-state acquisition period, making peak exercise measures difficult. Echocardiography can be used to measure LV function and chamber volumes during cycle ergometry, but its use is limited during arm cranking due to excessive motion and the need for a probe operator. Indirect Fick methods (e.g., CO_2 rebreathing) have been used during arm exercise, but due to the need for voluntary respiratory manoeuvres and a 3- to 5-min steady state, transient changes in LV function cannot be detected. In addition, only stroke volume and cardiac output are available using this technique. Impedance cardiography, though noninvasive and continuous, measures only impedance (aortic) derived stroke volume, is prone to respiratory and muscular artifact signal noise, and has not been consistently validated against gold-standard techniques during exercise.

The widespread use of these nuclear probes is limited by their cost (~$45 to $90K U.S.) and requirement for radionuclide RBC labeling and nuclear laboratory facilities for probe placement. Another commercially available miniaturized nuclear probe (Cardioscint, Oakfield Instruments, Eynsham, U.K.) does not require gamma camera-assisted chest placement due to positioning algorithm software (Breisblatt et al., 1991; Broadhurst et al., 1991). However, because the probe has a conical field of view (vs. the VEST™'s parallel field of view), it is slightly more susceptible to chest movement error, yielding a lower accuracy during exercise (Yang et al., 1993). Unlike the VEST™, it is not portable. However, it can record LV function data continuously on-line.

Care must be taken in obtaining quality background count data during exercise tests. As with MUGA tests, variations in background counts have a large impact on subsequent volumetric measures (Borer et al., 1977; Breisblatt et al., 1988b). If prolonged (>5 hrs) acquisitions are used, or if large changes are expected in lung perfusion or venous return, repeat background estimates should be performed. A further consideration involves repeated human RBC labeling and associated radioisotope dose burdens. This may introduce human ethics concerns into experimental designs involving repeated or serial interventions on separate days. In these cases, standards for annual dose limits must be considered and balanced with the anticipated experimental outcome.

We have demonstrated that a nuclear probe such as the VEST™, already accepted for LV function monitoring during daily activities, walking, and cycle ergometry, may also be useful in the noninvasive monitoring of LV function indices during arm exercise. Nuclear probes may be considered during arm exercise when other traditional measurement methods are inappropriate due to technical limitations.

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