A New Dual-Probe System for the Rapid Bedside
Assessment of Left Ventricular Function

Mark W. Groch, Stuart Gottlieb, Stephen M. Mallon, and August Miale, Jr.

University of Miami School of Medicine, Jackson Memorial Hospital,

A mobile dual-probe system has been developed for the rapid bedside measurement of left ventricular ejection fraction (LVEF) from the beat-to-beat count rate variations that occur during the transit of a single radionuclide bolus through the left ventricle (LV). Cardiac output, pulmonary blood volume, and left ventricular end-diastolic volume can also be calculated. The dual-probe system incorporates a central collimated probe for monitoring activity in the LV surrounded by an annular detector collimated in such a manner as to provide simultaneous real-time monitoring of the LV background activity. The LVEFs obtained from this system correlated well with LVEFs derived from conventional single-plane contrast angiography (r = 0.90) in a series of 33 patients with coronary artery disease. Positioning the dual probe over the midpoint of the LV is accomplished with standard M-mode ultrasound. Since the method is noninvasive and sensitive to volume changes in the LV, the dual probe is particularly useful for monitoring seriously ill patients as well as those with segmental wall-motion abnormalities.


In principle, radionuclide angiography can fulfill the need for a rapid noninvasive bedside method of quantitating cardiac function. However, current methods of obtaining accurate quantitative information on left ventricular (LV) performance (1–7) require the use of a scintillation camera with data-storage capabilities. Such equipment is currently difficult to bring to the bedside, and data analysis, moreover, is generally time-consuming.

Early single precordial scintillation detectors had the potential to provide information on cardiac function rapidly at the bedside, but the field of view of the first-generation probes encompassed a major portion of the heart, resulting in an extremely complex radiocardiogram (RCG) from which only gross pattern information could be obtained (8–11). The use of suboptimal emitters with equipment of insufficient frequency response further frustrated attempts to measure cardiac function. Recently, Steele et al. (12) have shown that a single bedside probe using the beat-to-beat variation in LV count rate could yield accurate quantitative information on LV performance after proper correction for background activity (13). This technique, however, requires two injections of a radioactive bolus through a central venous catheter and two positionings of the scintillation probe. To this extent, the technique is time-consuming and invasive.

A new dual-probe system has been developed that measures the left ventricular ejection fraction (LVEF) immediately after injection of a single radionuclide bolus into a peripheral vein. This dual-probe system displays the cyclic variations in activity during the passage of the radionuclide bolus through the LV, together with the background activity, on an optical strip chart recorder, which permits the LVEF to be read directly from the RCG using the
background level as a baseline. The LVEF can be obtained at bedside in 10 min and can be monitored frequently.

MATERIALS AND METHODS

The dual probe incorporates a central collimated detector that accepts gamma photons primarily from the LV, surrounded by an annular detector collimated in such a manner as to view tissue providing unwanted background, as shown in Fig. 1. The mobile probe stand carries a high-voltage power supply, discriminators, and dual count-rate meters with a capacity of 5 million counts per minute and selectable time constants down to 0.05 sec. Two distinct detector systems are thus provided and their outputs are displayed simultaneously on a dual-channel optical strip chart recorder. The recorder has a frequency response of 120 Hz; hence, it adds no losses to the recording of the RCG. A two-channel cassette recorder is also mounted on the probe stand so that probe data can be recorded simultaneously for off-line processing on an MDS Nova 1200 computer or replayed afterwards through the strip chart recorder at a higher than normal chart speed for examination of fine detail within the RCG.

The uniformity of the annular detector was tested by moving a 1-mCi point source of $^{99}$mTc around the periphery of the detector. Linearity of each detector was shown by employing a set of copper absorbers having from 0 to 100% absorption of a 1-mCi $^{99}$mTc source.

The midpoint of the left ventricle is located by a modified echocardiographic method, in which the major axis of the LV is recorded from the aortic root to the cardiac apex. The center of the LV is assumed to be immediately inferior to the mitral valve cusps, and the chest is marked for probe placement. The dual probe is centered over the LV and a 0.5-cm$^3$ bolus of 1–1.5 mCi of $^{99}$mTc-human serum albumin ($^{99}$mTc-HSA) is injected into an external jugular vein, immediately followed by a 5-cm$^3$ saline flush. As the bolus passes through the heart, dual traces (LV and background) are generated simultaneously on the strip chart (Fig. 1), with count rates of approximately 15,000–18,000 counts per second (cps) during the levophase of the LV RCG. Indium-113m-chloride may also be used in lieu of $^{99}$mTc-HSA, since it binds immediately to the plasma transferrin and remains within the vascular compartment (14).

A typical RCG from this system is shown in Fig. 2. Left ventricular ejection fraction may be calculated directly from the RCG using the relation

$$\text{LVEF} = \frac{\text{counts in peak} - \text{counts in nadir}}{\text{counts in peak} - \text{background}},$$

where peak and nadir correspond to end-diastole and end-systole, respectively. To calculate the cardiac output, an equilibrium LV count rate ($c_c$) is obtained after 10 min, and a blood sample is taken for measurement of equilibrium radioactivity concentration. Total blood volume (BV) is computed from the equilibrium concentration and the total amount of activity injected. Cardiac output (CO) may then be determined from

$$\text{CO} = \frac{(c_c)(\text{BV})}{A},$$

where $A$ is the area under the left ventricular time–activity curve during the first pass of the bolus (15). The mean pulmonary transit time is obtained by measuring the time interval between the washout of the background curve at 75% of its peak value (corresponding to ejection of the radioactive bolus from the right ventricle) and the peak activity within the LV (12). Pulmonary blood volume is also ob-

**FIG. 1.** Field of view of dual-probe detectors displayed over transverse section of thorax delineating left ventricular (horizontal lines) and background correction (oblique lines) components. Signal from background-detection system peaks initially as radionuclide bolus enters right heart. As bolus enters pulmonary circulation, little activity is seen in either detector. When it returns from pulmonary circulation, beat-to-beat variation in count rate, denoting LV filling and ejection, is observed in central detector signal. Background curve at this time provides baseline from which left ventricular ejection fraction (LVEF) can be obtained.
tained as the product of cardiac output and the mean pulmonary transit time.

The LVEFs obtained with this probe system were compared to those obtained using conventional single-plane contrast angiography in a series of 33 patients with documented coronary artery disease (CAD). In ten patients, LVEF values obtained using standard fluoroscopy and M-mode ultrasound to position to dual probe over the left ventricle were compared.

Computer processing. The greatest emphasis is placed on the LVEF determined directly from the strip chart record. However, computer processing can be employed for more detailed analysis of the RCG data. The RCG, recorded on cassette tape, is transferred into the computer through a second tape unit. Data are acquired at a rate of 25 frames per second, and the LVEF is computed by the method of Schelbert et al., in which the beat-to-beat variations from the LV are fitted to a sinusoid (4). The LVEF is then calculated utilizing the root mean square of the fitted sinusoid during the early mono-exponential portion of the LV washout.

For computation of the cardiac output, the RCG is replayed into the computer at a rate of 2 frames per second. The washout of the LV curve is then fitted to a gamma variate (16), and cardiac output is calculated from Equation 2. The mean pulmonary transit time and pulmonary blood volume are routinely available from the computer-processed information, as well as the rate of volume change (dv/dt).

RESULTS

Precise placement of the dual probe over the midpoint of the LV is essential for accurate quantitation of LVEF. The validity of the ultrasound (ECHO) technique for locating the midpoint of the LV was verified by comparing the LVEF determined after ECHO positioning of the dual probe with the LVEF determined after positioning by standard fluoroscopy on the same patient. The results for ten patients, given in Fig. 3, show that the methods correlated well (r = 0.98). However, the ECHO positioning is to be preferred, since it involves no additional exposure of the patient to ionizing radiation.

Left ventricular ejection fractions obtained from the dual probe for 33 patients with documented coronary artery disease (CAD) were compared with LVEFs obtained by standard single-plane contrast angiography. Patients with CAD were selected as they frequently exhibit abnormalities of ventricular
wall motion, in which case LVEF is difficult to quantify by other noninvasive techniques. In each of the 33 patients, the dual-probe LVEF was obtained directly from the strip chart by averaging the values obtained from 3–4 beats following the maximum count rate within the LV. The results are shown in Fig. 4, and correlation between the two methods is excellent \( r = 0.90 \). Computer-calculated LVEFs were used for reference only in this study.

In only one case did the dual probe grossly underestimate LVEF compared to the angiographic value (0.64 by the probe method and 0.82 by contrast angiography). Since this patient’s LV was extremely small, an inappropriately low level of cross-talk was measured by the annular background detector, thus reducing the patient’s LVEF. At the opposite extreme, the dual probe would tend to overestimate LVEF for an extremely large LV, since a portion of the LV would overlap into the field of view of the background detector. This overlap would tend to increase artificially the activity in the background detector, and result in an overestimation of LVEF. Even so, the dual-probe technique correlated well with single-plane contrast angiography over a wide range of ventricular sizes. The dual probe is equipped with interchangeable apertures of various diameters for the LV and background collimators. For this study, however, the geometry employed was fixed.

The LVEFs obtained with this system were found to be independent of the bulous injection site in three patients who were studied serially. A 1-mCi bolus of \(^{99m}\)Tc-sulfur colloid was injected at each of four sites within the central circulation; the results for one patient are shown in Table 1. The agreement among LVEFs determined for these four injection sites is good (average LVEF, 0.50 ± 0.02). The inherently superior efficiency of the probe system over a scintillation camera ensures a sufficient signal-to-noise ratio for accurate quantitation of LVEF, even with low concentrations of radiopharmaceutical. With this probe system, no significant difference in LVEF has been observed between peripheral-vein bolus injection and injection into the superior vena cava, right ventricle, or pulmonary artery. For the 33 patients reported here, dual-probe LVEFs were obtained using either jugular or central circulatory injection of the bolus. If the patient had had a catheter previously inserted, the injection was given into the central circulation; otherwise a jugular injection was used.

**DISCUSSION**

Since the acquisition of accurate high-frequency information requires the resolution of a single cardiac chamber, one section of the dual probe is centered over the left ventricle and collimated to maximize the count rate from this chamber. Due to the fixed collimator geometry and the variations in cardiac size and configuration within the thorax, it is impossible to confine the field of vision adequately by collimation alone. To compensate for this, an accurate assessment of the non-left-ventricular contribution to the total count from the LV detector is provided by the second detector system. If one assumes complete mixing and uniform distribution of the bolus within the left ventricle, the count rate from the LV, corrected for non-LV background, is proportional to the volume of blood within that chamber.

Certain parameters reflecting overall cardiac performance, and especially left ventricular performance as judged by the LVEF, provide useful prognostic information. Reliable noninvasive means of obtaining such data could also contribute significantly to the rational management of critically ill patients after acute myocardial infarction and provide a

**TABLE 1. LEFT VENTRICULAR EJECTION FRACTION FOR ONE PATIENT AFTER INJECTION OF THE RADIOACTIVE BOLUS AT VARIOUS SITES IN THE CENTRAL CIRCULATION**

<table>
<thead>
<tr>
<th>Location of bolus injection</th>
<th>Left ventricular ejection fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superior vena cava</td>
<td>0.48</td>
</tr>
<tr>
<td>Right atrium</td>
<td>0.51</td>
</tr>
<tr>
<td>Right ventricle</td>
<td>0.50</td>
</tr>
<tr>
<td>Pulmonary artery</td>
<td>0.51</td>
</tr>
<tr>
<td>Average</td>
<td>0.50 ± 0.02</td>
</tr>
</tbody>
</table>

**FIG. 4.** Comparison of LVEFs obtained by conventional single-plane contrast angiography and by dual-probe method. Line is that of identity.
means of assessing hemodynamic alterations after a myocardial revascularization or acute or chronic medical intervention. The use of the probe method for diagnosis of pulmonary embolism has already been described (12). The limitations of other non-invasive methods, particularly echocardiography, in determining these performance indices in a patient with CAD and segmental abnormalities of ventricular wall movement, are well known. In addition, alterations in the usual echocardiographic patterns of interventricular septal movement are associated with right ventricular volume overload and abnormal intraventricular conduction, which similarly restrict severely the usefulness of ultrasound as an indicator of left ventricular performance. Since the scintillation probe is sensitive to the count-rate fluctuations resulting from cyclic alterations in left ventricular chamber volume, dual-probe determinations are unaffected by left ventricular wall movement. Echocardiography, nevertheless, can provide valuable qualitative information about the cardiac performance, the anatomic characteristics of the chambers, and the condition of valvular structures, suggesting that the two methods can provide complementary information. Two cases are presented (Figs. 5 and 6) to illustrate the usefulness of the dual probe and also to emphasize the complementary relationship between the cardiac scintillation probe and the echocardiograph.

Limitations of the scintillation-probe technique are encountered in the presence of arrhythmias either of supraventricular or ventricular origin, since these produce an irregular cardiac rhythm and result in variable diastolic filling intervals. Extremes of left ventricular volume have produced RCG left ventricular ejection fractions that have, thus far, deviated from angiographic correlations in a predictable manner determined by the fixed geometry of the present collimating system. Studies are currently under way to utilize echographically determined left ventricular chamber dimensions as a means of more

FIG. 6. Left ventricular ejection fraction measured by contrast angiography was 0.49 compared to LVEF of 0.51 measured from this RCG. Echocardiogram at right shows limited sweep of ultrasound beam directed from region of anterior mitral-valve leaflet toward cardiac apex. There is normal movement of both interventricular septum and posterior myocardium. LVEF, estimated by cubing end-diastolic ventricular diameter (long vertical line) and end-systolic diameter (short vertical line), was 0.75, which is within normal range. Thus, unidimensional echocardiographic method overestimated true LVEF, since neither interventricular septum nor posterior myocardium moved abnormally. Coronary arteriography revealed critical narrowing of left anterior descending coronary artery distal to septal perforating branches. There was hypokinesis involving anteroapical portion of LV, evident upon left ventriculography.

FIG. 5. (Above) Radiocardiogram obtained while patient was in cardiogenic shock. Mean pulmonary transit time is prolonged (arrows), reflecting increased intracardiac transit time and large pulmonary blood volume. Despite clinical and hemodynamic evidence of cardiogenic shock, LVEF of 0.45 was obtained. This suggested large regurgitant volume. Intracoronary balloon counterpulsation and respirator were also being utilized and probably account for distortion in LV curve described by central detector. (Below) echocardiogram, performed with considerable technical difficulty, showing abnormal movement of anterior mitral-valve leaflet due to papillary muscle rupture. Coarse irregular notched appearance (arrow) is commonly associated with papillary muscle or chordal rupture.
optimally matching chamber size to the collimator geometry of the dual probe.

The probe system as a whole must be capable of accurately reproducing high-frequency information. Although single probes in the past have had sufficient ratemeter frequency response, they displayed the RCG on strip chart recorders with a relatively slow response. The effect has been to reduce the beat-to-beat amplitude (modulation) of the count rate variations from the LV. To compensate for this loss in modulation, the background time–activity curve has been artificially raised to restore the apparent modulation in the LV activity. A system with a lower-frequency response can be simulated with our equipment by increasing the ratemeter time constant to 0.1 sec. The effect of a slow-rise-time system on the RCG is shown in Fig. 7, which illustrates an RCG recorded and displayed at an appropriate ratemeter time constant of 0.05 sec for the central LV detector, and then replayed through the ratemeter with a time constant of 0.1 sec. Using the proper time constant (0.05 sec), the dual probe obtained an LVEF of 0.63 for this patient, and angiography obtained an LVEF of 0.61. When this RCG was replayed with a ratemeter time constant of 0.1 sec to simulate recording on a device of inadequate frequency response, the reduced LV modulation was apparent, and an LVEF of 0.45 was obtained using the probe's normal background baseline. If the baseline was artificially raised (Fig. 7B), a restored LVEF of 0.65 was obtained. It is not obvious that all patients' LVEFs could be restored in this manner, particularly if a patient's heart rate were increased. The background level necessary to obtain accurate estimation of LVEF would clearly be heart rate dependent with a slow-rise-time system, since the recorded modulation in the LV activity would decrease with increased heart rate. The high-frequency response used in our studies ensures accurate measurement of LVEF, independent of heart rate.

Note that on theoretical grounds it is impossible to say that the background and LV time–activity curves should consistently intersect at any one fixed point. The background level has been observed to vary from patient to patient with this system, and one fixed baseline level would not be suitable for all patients in all situations.

Compared with the scintillation camera, our detector, because of its superior photon-collecting efficiency, provides excellent statistics for calculation of LVEF. Count rates of 20,000 cps with 1.5 mCi of $^{99m}$Tc have been attained at the time of peak activity concentration within the LV. Time–activity curves generated from a scintillation camera with a region of interest encompassing the left ventricle contain a maximum of 2,500–3,500 cps during this portion of the RCG. Even LVEFs under 0.20 can readily be calculated from the dual-probe data. However, LVEFs under 0.10 are difficult to obtain even with good statistics, due to the reduced peak-to-nadir differences in count rate from the LV. Although probe devices inherently obtain better statistics, they do not provide visualization of the cardiac blood pool, and thus anatomic information may only be inferred from patterns exhibited in the RCG.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to W. L. Mortensen, E. L. Bialas, M. P. Buchin, and G. K. Lewis for their aid in the construction of this probe system; to W. White and J. R. Wolff for their valuable discussions and encouragement; and to A. M. Smudde, L. L. Walker, and F. R. Whitehead for their aid in the preparation of the manuscript. We also thank Nilza Kallos and Ali R. Ghahramani for their aid in the clinical evaluation of this system and Ernesto Garcia for his computer processing of the radiocardiogram data. Special appreciation goes to the late Stanley J. Draus.

This work was presented in part at the 22nd Annual Meeting of the Society of Nuclear Medicine, held in Philadelphia, Pa., June, 1975. Dr. Gottlieb is a Scholar in Radiologic Research of the James Picker Foundation.
REFERENCES


SNM TECHNOLOGIST SECTION
FOURTH ANNUAL WINTER MEETING

January 28–30, 1977 Hilton Hotel Las Vegas, Nevada

The Fourth Annual Meeting of the Technologists Section of the Society of Nuclear Medicine will be held in Las Vegas on January 28–30, 1977. The Las Vegas Hilton will provide excellent facilities for the meetings and a variety of entertainment in the evenings.

The workshops will be in the following areas: Education, Administration, Radioimmunoassay, and Imaging. There will be a "hands on" workshop with several portable scintillation cameras, a "hands on" RIA workshop which will cover a variety of procedures, and a session on making your own slide-tape presentations. Some information will also be presented on how to get local meetings approved for credit under the VOICE program. Many other topics of current interest will also be developed.

Continuing education certificates will be awarded.

For further information and registration forms, please contact:

Technologist Section, Society of Nuclear Medicine
475 Park Avenue South, New York, NY 10016