The Determination of Cardiac Output by the Dilution Method without Arterial Sampling

II. Validation of Precordial Recording

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Technics for determining the cardiac output by recording the dilution curve of injected iodinated I\(^{131}\) human serum albumin from precordial sites have been described. By viewing predominantly either the right or left side of the heart and by rapid delivery of the isotope, quantitation of the dilution curves for cardiac output has been possible without critical requirements for placement of the counter. In a series of 26 determinations in normal patients cardiac output values calculated from simultaneously recorded precordial curves and withdrawn arterial blood showed an average agreement within ± 8 per cent. In a smaller series of 8 determinations on patients in heart failure, an average deviation of ± 9 per cent was found.

In THE accompanying paper\(^1\) we have pointed out the necessary theoretical requirements for calculating cardiac output from precordial dilution curves and stated that accurate calibration and extrapolation of the curves are the prime requisites for successful quantitative measurements. In external counting technics, accurate calibration of the curve can be obtained only if the final dilution level is recorded from the same geometric sampling area as the primary dilution curve, so that effects of post-primary influx are minimized. Extrapolation problems can be resolved best by maintenance of a sufficiently high counting rate to record as great a number of clearance points as possible, and by reducing to a minimum the ratio of the extrapolated area to the measured portion of the dilution curve. In this paper we discuss the technics that during 7 years of study have been found necessary to or helpful in ensuring the accuracy of the radiocardiogram as a tool in the determination of cardiac output.

Methodology and Technics

Recording instruments were used, consisting of a sealer, Esterline-Angus recording meter,\(^2\) and a Berkeley\(^\dagger\) counting rate computer, whose scale was modified to record at intervals of from one third to 1 second. The scintillation counter was shielded, but further collimation of the heart was necessary and several types of collimators were explored for adaptation to this method.

Early in the work, when we attempted single-chamber recording, small-holed (\(\frac{1}{4}\)" to \(\frac{1}{2}\)" in aperture diameter and 4" in length) collimators were used. With the low efficiency and high target effect, the recording of good curves required that counter placement be critical. Prior to recording the precordial curve the patient was fluoroscoped, and a coin was placed over the desired spot on the precordium. Following the radiocardiogram a chest x-ray was taken with the patient in approximately the same position. Figure 1 shows the areas of the optimum sites from which good curves were obtained in many trials. This diagram suggested that good curves could be recorded from the mid-lower portions of both sides of the precordium. Curves taken from high or extremely low positions on the right side were poor. In spite of careful fluoroscopy, for a reasonably accurate placement, positioning of the counter introduced errors in the calculation of flow largely because of the difficulties in eliminating the post-primary influx. For this reason the approach of heavily collimated, critical placement was abandoned.

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\(^{1}\)Esterline-Angus Co., Inc., Indianapolis, Ind.

\(^{\dagger}\)Model 1600, Berkeley Scientific Co., Richmond, Calif.

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Collimation

In general, with collimation we attempted to match the dominant chamber to be viewed in respect to its anatomic location beneath the chest wall while restricting to a minimum radiation from extraneous sources. Figure 2 shows the dimensions and efficiency characteristics of 2 collimators tested. The plots of superimposed curves represent the counting rate efficiency recorded from a radioactive point source moved perpendicular to the axis of the collimator at varying distances from the aperture. The collimator on the left was used in the majority of the studies reported in this paper and was found satisfactory, that on the right is of the highly collimated type used previously for single-chamber determinations.

Placement of Counter

Although dilution curves can be inscribed from varying sites over the precordium and posterior thorax, curves from which quantitative cardiac output values can be accurately calculated must meet certain criteria. From theoretic considerations, when multichamber recording is desired, either the right or left heart dilution should be emphasized and the contribution of the other side minimized.

Curves recorded from the mid-precordium showing approximately equal diluting volumes between the right and left sides of the heart are usually unsatisfactory. The disadvantage of these curves lies in the uncertainty of predicting the final extrapolation. Since such curves exhibit the summation of 2 clearance chambers of completely different exponential rates, this summation will not be a simple exponential decline, so that extrapolation on this basis will not be valid.1

Although positioning of the counter to accentuate the dilution curve from one side of the heart is essential for good quantitation, each side of the heart offers its peculiar advantages. From the

![Diagram of precordium](http://circ.ahajournals.org/)

**Fig. 1.** Diagram of precordium. *Lined areas,* satisfactory curves recorded with highly collimated system. *Crossed area,* double peak curves even with high collimation.

![Dimensions and efficiency characteristics of 2 types of collimators](http://circ.ahajournals.org/)

**Fig. 2.** Dimensions and efficiency characteristics of 2 types of collimators representing moderate (*left*) and high (*right*) collimation. Left collimator was used in the correlation study and right collimator was utilized for earlier single-chamber attempts.
right side there is a higher concentration of relatively undiluted radioactive material, giving in increased sensitivity, a large ratio of the measured to extrapolated portion of the curve, and usually a short but definite final extrapolation line. Recording from this side however, has the disadvantage that possible poor mixing may be unrecognized and abnormally high values may be recorded. The left side offers the advantages that there are usually more recorded points on the descending limb of the curve for extrapolation, mixing problems are minimal, and from a clinical point of view more heart diseases are associated with left-sided enlargement and more discrete left chamber separation is thus possible. On the other hand, the left side has the disadvantage of lower sensitivity in the counting rate due to dilution and distance, and the extrapolated area is usually greater than from the right.

In figure 3 are shown 2 curves of the same patient recorded from each side of the precordium with values of cardiac output that are almost identical. From the right side there is an abrupt, early, rapid rise to a maximal value within a few seconds followed by a rapid decline in concentration which is interrupted on the descending slope by a small deviation and a further fall at a slower rate. This latter slower portion of the curve indicates clearance of the left chambers, and its size in proportion to the whole curve depends upon the amount of left chamber viewed by the counter in this position. This left heart contribution is usually easily distinguishable from the final surge due to recirculation of the injected isotope.

In curves from the left side the initial onset may be rapid and abrupt, but after a small primary rise a succeeding larger, steep curve reaching a peak later on the time axis is seen. Then follows a smooth, uninterrupted descent as clearance from the left side continues before the recirculation wave is identified. In none of the curves recorded from either side of the heart have we been able to identify small waves of activity on the descending limb indicative of coronary circulation effects. 7

A serious source of error in placement of the counter may arise whenever the counter is focused over the higher portions of the right inflow tract, i.e., superior cava or high right atrium. In this situation, the counter does not view a homogeneous concentration and thus records abnormally tall, steep, narrow, single-phase curves. These curves are indicative of a strong radioactive source which has not been diluted by a mixing process and exhibits laminar rather than turbulent flow. Because of the narrowness of these curves, the area is small and quantitation will usually result in
spuriously high calculations of cardiac output. Figure 4 illustrates the effects of recording from a point too high in the inflow system. The same type of error may be present if the injected substance is delivered into the left ventricle too close to the outflow tract via left atrial puncture, and concentrations are determined from sampling the blood of the peripheral arteries. Curves recorded from low positions on either side would exhibit in many instances contributions from other large vascular pools, such as the liver.

At the present time it is our practice, whenever
right predominant curves are desired, to place the counter approximately perpendicular to the chest wall without lateral rotation over the fourth intercostal space or fifth rib at the right parasternal margin. To record left predominant curves the counter is usually placed at the point of the maximal apical impulse with the counter rotated somewhat medially, perpendicular to the chest wall. Minor placement variations may be made depending on the chest contour and the heart size. Empirically, in thin people with centrally located hearts we have found the right predominant curve more satisfactory, and in the more obese, stocky person the left predominant curve appears preferable.

Delivery of Isotope

Early in our studies it became evident that not only did the site of precordial recording and type of collimation affect the radioangiogram, but also the type of delivery of the isotope into the circulation had a significant influence on the form of the recorded curve. Figure 5 illustrates the effects of the volume injected and of flushing on curve form. These curves were obtained over the same left precordial site on a normal subject within a few minutes of each other. The volume injected and the rate of delivery were varied and the results are representative of other similar trials. In figure 5, bottom, left, the usual technic was followed, of a 3 ml. volume followed by a 10 ml. saline flush. A "normal" left predominant curve resulted.

In figure 5, top, right, the same volume without a flush resulted in a less discrete curve; the summit is not displaced in time, but the final slope of clearance is slower. In figure 5, bottom, right, an 8 ml. dose without a flush gave a slower rise, a summit displaced later in time, and a much delayed final clearance.

Flushing acts as much to compress the trailing end of the volume injected into a smaller bolus as to speed its entrance into the right heart. Although the form of the curve should theoretically make little difference in its quantitation, from a practical consideration the rate and degree of fall of the final slope influence not only the accuracy of the extrapolation but also the percentage extrapolated to the total area. To obtain optimum characteristics of the curve we have found flushing to be of great importance. In figure 5 the per-
percentages of extrapolated to total area (bottom left, top right and bottom right, respectively) are 17, 34, and 39. The larger the extrapolated area becomes, the less is the accuracy of the method.

The effects of position of the patient were also studied, and consistently good results were obtained by having the patient seated in a reclining chair with the arm into which the injection is to be made elevated and relaxed (fig. 6). Usually from 2 to 3 ml. labeled albumin containing a minimum of 5 μc. and a maximum of 180 μc. are rapidly delivered in 1 stroke, and followed immediately by a forced flush of 10 ml. saline through a 3 way stopcock. When the patient is recumbent, it is important to avoid axillary constriction. The arm should not be raised immediately after injection, as trapping at the thoracic inlet has frequently been encountered. Whenever repeated determinations at successive intervals over a short period of time are necessary, the dose of labeled albumin has been approximately doubled for each succeeding injection, to insure sufficient statistical accuracy over the previous background. This has limited the number of determinations that can be made at any one sitting, but better defined curves have resulted.

Procedure

For a test of the validity of our theoretical conceptions, a series of patients was studied in which the cardiac output values calculated from dilution curves recorded from the precordium were compared with simultaneously recorded curves obtained from blood withdrawn from the brachial artery. The patients were allowed to rest quietly in the laboratory armchair, while a no. 18 Courand needle was inserted into the basilic vein of one forearm for injection and another Courand needle was placed into the brachial artery of the other arm for recording the peripheral dilution curve, as described previously. Since the previous report of our arterial puncture technic, improved sensitivity of recording has been obtained by the use of a channeled sodium iodide crystal through the center of which is inserted a siliconed stainless-steel tube. Successful curves recorded with this channeled crystal have been obtained with only 20 μc. of labeled albumin. From 20 μc. to 120 μc. contained in a 2 to 4 ml. volume were rapidly injected and followed by the usual 10 ml. saline flush. Both curves were continued until well after the primary circulation, to insure the identification of any post-primary influx on the precordial curve and to identify recirculation on both curves. Thus one could compare accurately a precordial curve with the dilution curve of withdrawn arterial blood. It had been shown previously in this laboratory that arterial dilution curves

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<th>Patient no.</th>
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<th>Precordial cardiac output (L./min.)</th>
<th>Arterial cardiac output (L./min.)</th>
<th>Deviation from arterial cardiac output (%)</th>
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Average deviation ±8%.

recorded in this manner checked well in animals when compared to measurements obtained with aortic rotameters and in man when compared with cardiac outputs obtained by cardiac catheterization.

Results

Normal Subjects

In 17 patients, 26 determinations were performed, of which 10 were right predominant curves and 16 were of the left predominant type. In table 1 are shown the data from the entire series of patients not in heart failure. The range of cardiac output values was from 8.3 liters per minute to 3.4 liters per minute, with correlation deviations of the precordial from the arterial curve of from minus 13 to plus 28 per cent, with an average of ±8 per cent. In this laboratory previous correlations of the arterial dilution curve with the standard Fick procedure with patients in the basal
state have shown an average deviation of ±8 per cent between the Fick and dilution output calculations. In this series no attempt was made to maintain a constant basal state, and several patients were studied in the afternoon after lunch. Thus, since the first and second runs in patients of this series were not expected to be the same, the second trial served as a separate determination of comparison between the precordial and arterial values rather than a comparison of the 2 separate runs against each other. Maintaining good flow through the arterial needle of the brachial puncture after some time had elapsed in the study was a problem in the occasional case and may have accounted for the larger errors in which the precordial value exceeded the arterial value. The abnormally large deviation in patient no. 18 has been attributed to this cause.

Cardiac Patients

Although fewer studies have been performed on patients in severe cardiac failure, our results have been as satisfactory as those in the normal group. A typical dilution curve from the left side is shown in figure 7 and illustrates the characteristic slow dilution and long extrapolation required when the cardiac output is low. Because of the tendency of the downstroke of the primary curve to merge with recirculation, fast injection, rapid flushing, and adequate isotope doses are necessary

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<td>3.1</td>
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</table>

Average deviation ± 9%.
to give high statistical accuracy in recording the descending slope.

Table 2 shows compilation of 8 runs on 4 patients in cardiac failure. It should be noted that the left chamber has been selected as the site in most instances, although figure 8 demonstrates that it is possible to record from the right chamber with adequate reliability.

In table 3 are summarized all data, from both normal subjects and subjects with cardiac disease, in a condensed fashion; it can be seen that only 2 of 35 determinations show deviations over 17 per cent.

Conclusions

If the analytical considerations can be fulfilled, and the counter can be placed on the precordium in such a way as to emphasize a predominant chamber, successful clinical studies of cardiac output can be made independent of critical placement of the counter. The necessary precautions have been described to accomplish this, and correlation studies in patients showed a high degree of accuracy when cardiac output values obtained by this method were compared with those calculated from peripheral arterial dilution curves.

Summary

Technics have been discussed that are important in recording precordial dilution curves from which cardiac output values can be calculated.

Proper placement of the counter is important, but is not critical, so long as the right or left side of the heart is made predominant and the effects of the other chamber are minimized.

In a series of patients the precordial curves are compared with curves obtained by brachial artery puncture; good agreement was obtained with an average deviation of the precordial from the arterial curves of 8 per cent.

This technic may be a useful adjunct in the study of cardiovascular diseases, since it involves very little cooperation from the patient and determinations can be made with ease.

Summario in Interlingua

Es discutite technicas de importancia in le registration de precordial curvas de dilution como base del calculation del rendimento cardiac.

Le correcte placamento del contator es importante sed non de importancia critica, si predominancia es attribuite al latere dextere o al latere sinistre del corde, con minimisation del effectos del camera al latere contrari.

In un serie de patientes le curvas precordial eseva comparete con le curvas obtenite per punctura del artery brachial. Le concordantia eseva bon, con un deviation medie del curva precordial ab le curva arterial de 8 pro cento.

Iste technica va possibilemente esser un adjuncto utile in le studio de morbos cardiovascular, proque illo require pauc cooperation del parte del patiente, e le determinationes se face con facilitate.

References


The Determination of Cardiac Output by the Dilution Method without Arterial Sampling: II. Validation of Precordial Recording
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