Quantitative Radiocardiography
II. Technic and Analysis of Curves

By L. Donato, M.D., D. F. Rochester, M.D., M. L. Lewis, M.D., J. Durand, M.D., J. O. Parker, M.D., and R. M. Harvey, M.D.

On the basis of theoretical considerations previously presented, a method has been developed for the measurement of cardiac output, right ventricular and pulmonary blood volumes. The present paper deals with a description of the instrumentation and of the procedure employed to secure radiocardiograms and with the technic of analysis of the curves.

Method

Instrumentation

Time activity curves are recorded by means of a scintillation counter, with a NaI crystal 1 1/2 inches in diameter, located in a lead collimator with a straight bore of the same diameter. The crystal surface is recessed 10 cm. from the external opening of the collimating channel. The efficiency distribution for this collimated counter is represented in figure 1 of the previous paper. This distribution was determined by means of a point source suspended in a cylinder of water to simulate the chest. With this collimator, activity anywhere in the four heart cavities may contribute to the counting rate. Since the fraction of the lungs included in the field is small and the counting efficiency of this fraction is considerably less than that of any heart cavity, the contribution of the lungs to the precordial counting rate is minimal.

Pulses from the photomultiplier tube are amplified and fed into a counting ratemeter and into a scaling circuit. The output of the ratemeter is fed into a multichannel electronic recorder, with monitoring oscilloscope, which is adjusted so that there is approximately 1 mm. paper deflection for 800 counts per minute when the 100,000 cpm scale of the ratemeter is utilized. The response both of the ratemeter and the recorder is linear. A paper speed of 2.5 cm. per second is generally used for recording the curves, with time lines inscribed every 0.1 second.

A signal from the scaling circuit also may be fed into the electronic recorder, and a pulse recorded every time the scaler has collected a preselected number of counts. When tracings are recorded with this additional system, the paper speed is increased from 2.5 to 10 cm. per second.

Procedure

The subjects are catheterized in the morning in a fasting state, without premedication, according to the procedure used in this laboratory. In most cases, one double-lumen No. 9 catheter is introduced into the right pulmonary artery, just beyond the cardiac border, and a No. 6 catheter into the midportion of the right atrium. A Cournand arterial cannula is introduced into a brachial artery. The counter is set in place over the center of the heart shadow, as determined by fluoroscopy, at a distance of 2.5 cm. from the skin.

Under sterile conditions RIIHSA is diluted so that 30 to 40 μc. of 131I are contained in 0.5 ml. of solution. Semi-automatic syringes are used for injection of radioactivity. The syringe is adjusted to deliver the desired injectate, and is connected via a three-way stopcock to a reservoir syringe containing the radioactive solution. This system permits repeated injections of tracer solution, the volume of which is reproducible within two parts in one thousand.

The semi-automatic syringe and reservoir are connected to the right atrial catheter and shielded. After measurement of the background counting rate, three aliquots of solution, 0.5 ml. each, are rapidly injected into the catheter. This volume of injectate has been found sufficient to completely flush and overfill a No. 6 catheter. Overfilling of the catheter results in the appearance of a miniature transit curve on the monitoring oscilloscope. When distribution of the tracer in the circulation is essentially uniform (approximately 1 minute), 5 ml. of arterial blood are drawn into a syringe containing heparin in its dead space; simultaneously, a precordial counting rate is recorded on the scaler in order to establish a new baseline. The ratemeter time constant is first set at 1.6 seconds (100,000 cpm scale) and the background activity recorded. After 10 seconds the time constant set-

From the Department of Medicine, Columbia University, College of Physicians and Surgeons and the Cardio-Pulmonary Laboratory of the First Medical and Chest Services, Columbia University Division, Bellevue Hospital, New York, New York.

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ting is switched to 0.37 second, then 0.5 ml of RIHSA solution is injected rapidly, and the curve is recorded together with the electrocardiogram.

One minute after inscription of the curve, another arterial blood sample is taken simultaneously with a counting rate on the scaler. The contents of the catheter are then aspirated, and the precordial count is repeated. The detector is then moved over the thigh, and a 1-minute counting rate measured.

Two milliliters of plasma are obtained from each arterial blood sample, and the radioactivity is determined by means of a well scintillation counter.

A volume of RIHSA solution equal to that injected for a single curve is quantitatively diluted with distilled water (1/1000) and duplicate 1-ml. samples are assayed. The injected activity is thus obtained, as counts per minute.

When Kr\textsuperscript{85} is utilized, the catheterization and collimation techniques are the same as for RIHSA studies. The right atrial catheter is filled with 1.5 ml of Kr\textsuperscript{85} solution. Right selective tracings are obtained by injecting 0.4 to 0.5 ml of solution, equivalent to 1 to 1.5 me of Kr\textsuperscript{85}. The ratemeter and recorder settings are similar to those used for RIHSA radio cardiograms.

**Morphology of Curves**

**RIHSA Radiocardiograms**

The exact time of injection of the tracer can be identified on the tracing (fig. 1), since the rise in the counting rate is immediate. A peak is reached within one heart cycle in normal subjects, and occurs in relation to the transfer of the major fraction of activity from the atrium to the ventricle, since the counting efficiency is higher for the more anterior chamber. The counting rate drops from the peak, reaching immediately, or after one beat, an exponential downslope. Cyclic variations in counting rate, synchronous with heart events, are often identifiable on this downslope, despite the damping effect of the ratemeter. These are a result of the discontinuity of ventricular emptying and of the displacement of the heart position during the heart cycle. The downslope appears linear in the semilogarithmic plot (fig. 2) but the straight line is interrupted at the time when activity appears in the left side of the heart. From then on, the recorded counting rate is equal to the sum of the decreasing residual activity in the right ventricle and of activity in the left cavities. If the exponential downslope of the first curve is extrapolated, the difference between the recorded curve and the extrapolated function gives the transit curve through the left cavities. The second peak, due to the passage of the tracer through the left side of the heart, is of smaller amplitude than the first, as a result of dispersion of the tracer and of the lower counting efficiency for the left heart cavities. The downslope of the left curve is interrupted at a time when the initial amount of tracer recirculates through the right heart. In a normal subject the over-all duration of the curve, from injection to the first detectable recirculation is of the order of 14 seconds.

**Kr\textsuperscript{85} Radiocardiograms**

The ascending part of the Kr\textsuperscript{85} radio cardiogram (fig. 3) is identical to that of a RIHSA radio cardiogram except that the peak counting rate of the former is one quarter to one third of the first peak of the RIHSA radio cardiogram. The peak is followed by a decrease of the counting rate that reaches a steady level within 3 to 6 seconds. The final steady level may coincide with the background prior to inscription of the curve or may be slightly higher. The difference, when present, is presumably due to the contribution to the precordial counting rate of Kr\textsuperscript{85} in the lungs, since this tracer is almost
quantitatively transferred to the alveoli on the first passage through the pulmonary circulation.

Analysis of the Curves and Calculations
The curves are analyzed by reading at every 0.1 second the height of the deflection in millimeters above the background. The latter is obtained by averaging over several seconds the ratemeter trace immediately before the curve. The net deflections are plotted on semilogarithmic paper against time on the linear abscissa. The downslope of the second peak is fitted with a single exponential.

Calculation of $Q_{RIHSA}$

The total area, $A_T$, under the RIHSA radio-cardiogram is calculated as:

$$A_T = A_1 + A_2$$

where $A_1$ is the sum of the deflections at every 0.1 second from the time of injection to the time when the downslope of the left curve deviates from the imposed exponential; and $A_2 = R_{KL}/k_L$, where $R_{KL}$ is the deflection in millimeters at the time of deviation, and $k_L$ the slope of the imposed exponential in tenths of second. $Q_{RIHSA}$ is obtained as:

$$Q_{RIHSA} = \frac{600 \ I \ W_T}{r \ A_T} \text{ ml./min.}$$

where 600 is the time conversion factor, from tenths of second to minutes; $I$ is the injectate measured in counts per minute; $A_T$ is the total area as defined above in millimeters multiplied by tenths of second; $r$ is the conversion factor, expressed as counts per minute on the scaler in vivo per millimeter deflection on the tracing, and $W_T$ is the total effective volume. $W_T$ is calculated as:

$$W_T = \frac{R_{eq} H}{c_{eq}}$$

where $c_{eq}$ is the counting rate in counts per minute per milliliter of blood, in the sample taken after recording of the curve; $R_{eq}$ is the net counting rate from activity in the heart.
cavities at the time of sampling for $c_{eq}$; and H is the fraction of the total precordial counting rate coming from the heart cavities (see equation 7 of first paper of this series).

If the final precordial counting rate is measured with a filled catheter in place, to obtain $R_{eq}$ both the background of the counter, $BG_s$, and the counting rate due to the presence of the filled catheter in the field, $BG_c$, have to be subtracted from the total precordial counting rate. $BG_c$ is calculated on the basis of the general relationship between observed external counting rate, $R$, and simultaneous net blood counting $\bar{e}$:

$$R = W\bar{e} + BG_s + BG_c$$  \hspace{1cm} (4)

where W is the effective volume seen by the counter, and includes the contribution of the paracardiac tissues in the field. Two simultaneous equations of type (4) can be set up for the $R$ and $\bar{e}$ values before and after the curve. Solving them for $BG_c$:

$$BG_c = \frac{(R_1 - BG_s) - (c_1/c_2)(R_2 - BG_s)}{1 - (c_1/c_2)}$$  \hspace{1cm} (5)

Equation (5) becomes of little use when the ratio of $c_1$ to $c_2$ becomes large, as happens after repeated radiocardiograms. In this instance, a small error in the ratio may cause a large error in the calculated $BG_c$. Therefore, if multiple radiocardiograms are drawn, it is advisable to measure directly the catheter background by taking the difference in the precordial counting rate before and after withdrawal of the catheter from the counter field.

**Calculations of Right Ventricular Volumes**

In order to correct for the ratemeter damping, equation (17), given previously, is modified and rearranged as follows:

$$Y_t = R_t - \Delta R \frac{\tau}{\Delta t}$$  \hspace{1cm} (6)

where $\tau$ is the ratemeter time constant setting during recording of the curve (0.37 second); $\Delta R$ is the difference between two values of the net ratemeter deflection, $R_t$, separated by a $\Delta t$ interval; $Y_t$ is the deflection in millimeters at time t, now corrected for the damping effect.

By use of a $\Delta t$ interval of 0.2 second, equation (6) is reduced to:

$$Y_t = R_t + 1.85 \Delta R$$  \hspace{1cm} (7)

The values of $Y_t$ thus obtained are plotted on the same semilogarithmic paper on which $R_t$ has been plotted (fig. 4). The scaler tracings are analyzed as described by Giuntini et al. The time interval, $\delta$, between two consecutive signals is read in

*Figure 3*  
$Kr^{85}$ radiocardiogram obtained by injection of tracer into the right atrium of a patient with a normal cardiovascular system. Time lines are inscribed every 0.1 second.
seconds with an approximation of 5/1000 of a second. The corresponding deflection in millimeters is obtained as:

$$Y_t = \frac{60K}{8} r$$

where $K$ is the preselected scaling factor and $r$ is the conversion factor from counts per second to millimeters. The previous background is subtracted from the values of $Y_t$ thus obtained. The resulting deflections are plotted on the same graph as the corrected ratemeter readings (fig. 4).

In order to calculate $R$ the values of $Y_t$ obtained by the correction of the ratemeter tracings are averaged within each heart cycle, taking an electrocardiographic tracing as a reference. In most instances, it is convenient to consider the cycle as starting with the P wave in the electrocardiogram. The logarithm of the averages obtained is plotted against the number of beats, as in figure 4, and the steepest line, going at least through three consecutive points is calculated. From the value of the regression coefficient $b$, the rate of emptying, $R$, is calculated as:

$$R = 1 - e^{-b}$$

In the case of the $Y_t$ values obtained from the scaler tracing, the regression line is also calculated from the logarithm of the $Y_t$ values, as the steepest line fitting at least three heart cycles. In this case, the regression coefficient is expressed per second, and it has to be converted to beat units. Ventricular volumes are calculated from the stroke volume and the emptying rate. The apparent ventricular diastolic volume, VDV, and ventricular

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**Figure 4**

From left to right, semilogarithmic plotting of (a) direct and corrected ratemeter readings, (b) corrected ratemeter and scaler readings, (c) corrected ratemeter readings and their averages beat by beat. The curves were obtained from a RIHSA radiocardiogram in a patient with a normal cardiovascular system. Only the right ventricular portion of the curve is represented.
residual volume, VRV, are calculated as:

\[ VDV = \frac{SV}{R} \]  
\[ VRV = VDV - SV \]  

When R is obtained from K_{r^{88}} radioangiograms, the value of SV to be introduced in the calculation is derived from a direct Fick determination, or from the RIHSA radiocardiogram.

**Calculation of the Pulmonary Blood Volumes**

The mean pulmonary circulation time is obtained from the RIHSA radiocardiogram by subtracting the extrapolated right exponential downslope from the corrected ratemeter curve in order to obtain the isolated left curve (fig. 5). The first heart cycle following injection during which tracer is ejected from the right ventricle is taken as \( t_0 \). The heart cycle during which the total ratemeter tracing deviates from the right exponential is \( t_a \).

The heart cycle during which the left curve reaches a peak is \( t_p \). If the left curve shows a plateau, \( t_p \) is taken at the midpoint of the plateau. The pulmonary blood volume is calculated on the basis of equation (20) presented in the first paper of this series.\(^1\)

**Summary**

A technic for obtaining radioangiograms has been described and a method of analysis of the curves presented.

**References**

