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HOMER R. WARNER and ALAN F. TORONTO

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Quantitation of Backflow in Patients with Aortic Insufficiency Using an Indicator Technic

By Homer R. Warner, M.D., Ph.D. and Alan F. Toronto, M.D.

A method is reported which permits the estimation of the time-course of backflow velocity in the descending aorta of patients with insufficiency of the aortic valve. Instantaneous back-velocities in excess of 100 cm./sec. have been observed. Evidence suggesting the existence of an oscillation in aortic flow during diastole in some patients is presented. An index to the "volume of backflow per stroke" is described.

THE recent advancements in heart surgery have stimulated the development of technics for quantitating the hemodynamic abnormalities which accompany valvular heart disease.[1-3] In this report a method which permits the determination of the time-course of back-flow velocity in the descending aorta of patients with insufficiency of the aortic valve is described. Data concerning the shape and magnitude of this velocity-time function in patients and dogs with aortic insufficiency have been obtained.

Theory

A single particle of dye injected into the descending thoracic aorta of a patient with an insufficient aortic valve might be expected to travel forward (away from the heart) during systole and backward during diastole. The distance by which the forward travel exceeds the backward travel is represented by a in figure 1. It is evident that if the particle is injected into the aorta at the onset of systole at a point b cm. distal to the origin of the left subclavian artery, the dye will not enter the subclavian on its first circulation since its forward travel exceeds its backward travel. However if the particle is injected at time t_1, it will get back proximal to the origin of the left subclavian and on the next systole will be distributed to the left subclavian and to the descending aorta in proportion to the flow.

If the injection be made at a constant rate over an interval of time from t_1 to t_3, the fraction of the dye injected between t_1 and t_2 will get back proximal to the subclavian origin. This is designated the α fraction. That fraction injected between t_2 and t_3 will not contribute to the subclavian aliquot. From this diagram it is evident that α is a function of the time of onset and duration of the injection as well as the distance (b) from the origin of the left subclavian to the site of injection.

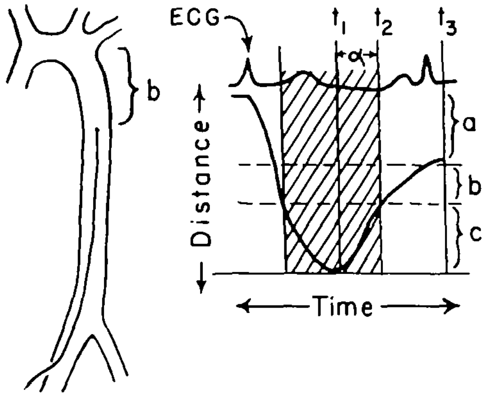

Fig. 1. Diagram showing theoretic course a particle of blood might take during a single cardiac cycle in the aorta of a patient with aortic insufficiency.

An equation derived in the appendix demonstrates that α may be obtained as the ratio (R) of the area under the curve of dye concentration recorded as a function of time at the left radial artery to the area of a similar curve at the femoral artery (R = *area radial curve/area femoral curve*). Experimental data will be presented which support this equation. Measurement of this parameter (R) as a function of time in the cardiac cycle and position in the aorta yields pertinent data concerning the contour and magnitude of backflow velocity as a function of time in this segment of the arterial bed in patients with aortic valvular insufficiency. (See appendix for derivation of equation relating R to backflow velocity.)

From the Department of Physiology, Latter-Day Saints Hospital and University of Utah, Salt Lake City, Utah.

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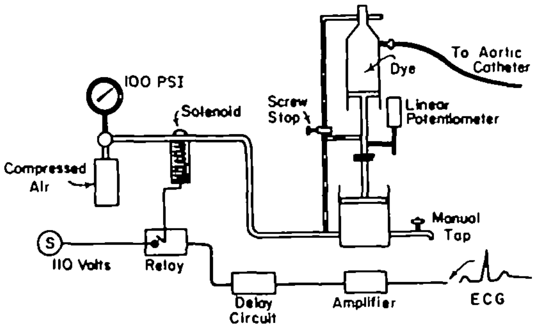

FIG. 2. Diagram of the device used to inject a small amount of dye at a specific time in the cardiac cycle.

METHOD

The procedure to be described has been performed on 17 subjects without evidence of aortic valvular disease, on 32 patients with various degrees of insufficiency of the aortic valve, and on 8 dogs before and following the incision of one cusp of the aortic valve to the ring.

Following injection into the descending thoracic aorta of 0.15 to 0.62 ml. of the dye solution (15 mg./ml.), the concentration of Evans blue dye is detected continuously and simultaneously in blood from the left radial and left femoral arteries using cuvette oximeters.[4] The output voltage of each oximeter is fed to a logarithmic amplifier[5] whose output becomes a linear function of dye concentration.[6] Galvanometer deflections are recorded photographically on 11.5 inch width kymograph paper at a speed of 5 mm./sec. using a Waters camera.

An arterial catheter† (80 cm. long, 0.5 mm. I.D. and 1.0 mm. O.D.) is advanced into the thoracic aorta through an indwelling thin-walled 18 gage needle in the right femoral artery until its tip lies near the origin of the left subclavian artery. This will be about 55 cm. from the needle hub in the average-sized adult. The proximal end of the catheter is connected by way of a stainless steel tube to an injection device shown diagrammatically in figure 2, and its operation is described below.

On closing a manual switch, the next R wave of the electrocardiogram is amplified and fed into a calibrated adjustable delay circuit.‡ After being delayed the signal operates a relay which opens the solenoid valve allowing compressed air at 100 p.s.i. pressure to drive the piston which is coupled to the plunger of the stainless steel dye syringe. The amount of dye injected is determined by the setting of the screw stop (0.31 ml./turn). The

*Made by Engineering Specialty Co., Salt Lake City, Utah.

†Made by Mr. Albert Afford, Barrington, N. J.

‡Engineering Specialty Co., model DC-1.

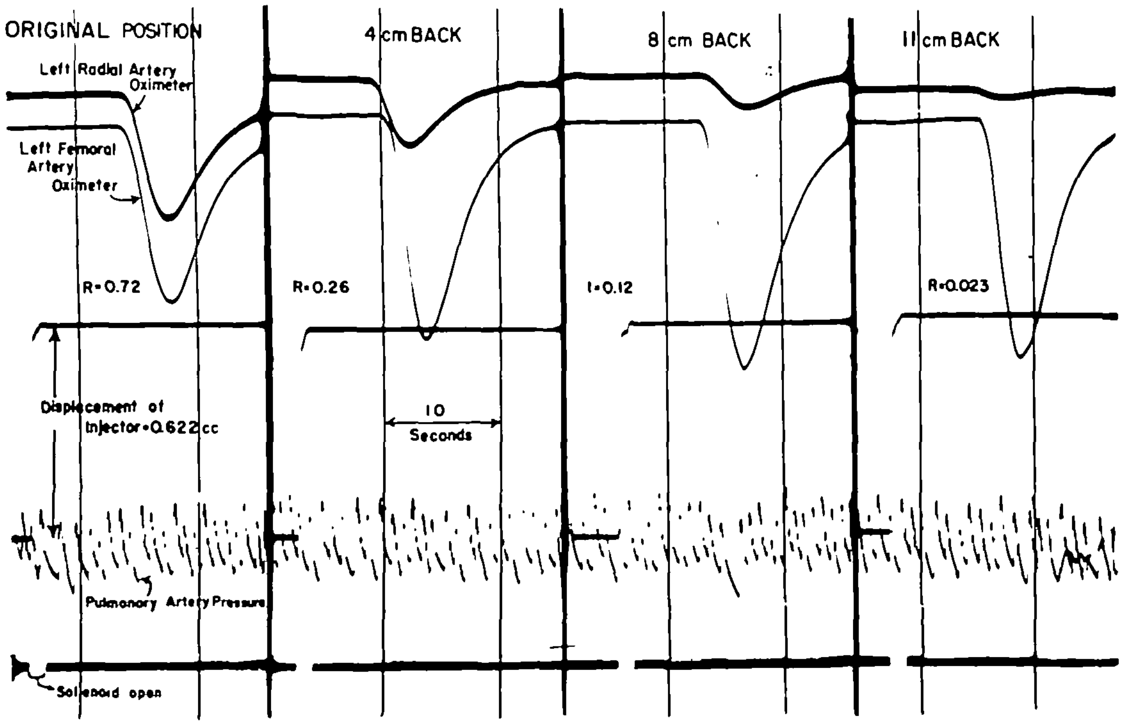

FIG. 3. Direct recordings of the time-course of dye concentration in the femoral and left radial artery blood of a patient with insufficiency of the aortic valve.

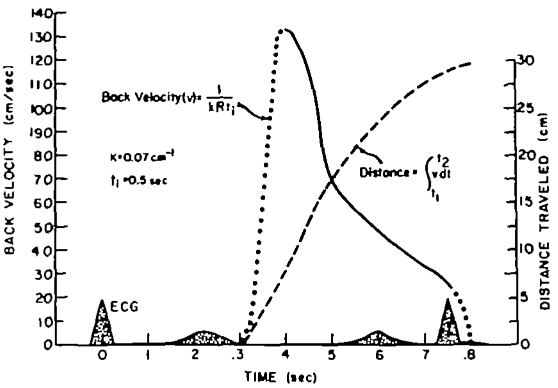

FIG. 4. *Solid line,* calculated back-velocity as a function of time, in patient with severe aortic insufficiency. Values for velocity near the beginning and end of diastole (*dotted line*) are extrapolations based on the assumption that reversal of flow occurs at these two points in the cycle. *Broken line,* distance traveled by blood column.

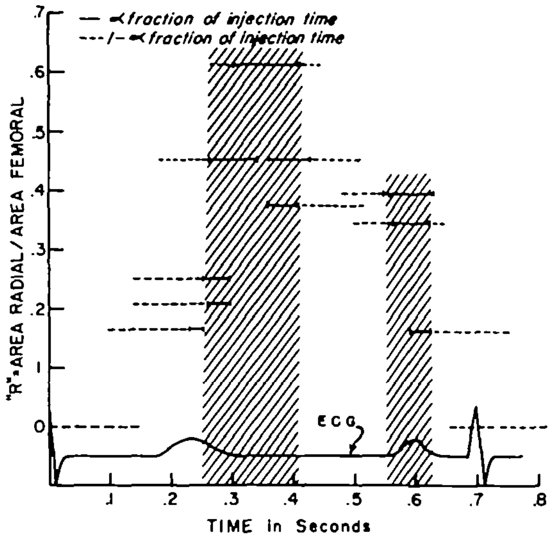

FIG. 5. Plot of *R* versus time in cardiac cycle for 11 injections in patient with aortic insufficiency. Vertical position of a line corresponds to value of *R* obtained for the injection whose timing is indicated by the horizontal position of the line. *Shaded bands,* discussed in text.

plunger is coupled to a linear potentiometer to permit recording of the injection. Multiple injections can be made without reloading the syringe by simply releasing the pressure with a manual tap and resetting the screw stop.

When the catheter and needles are in place, the following sequence is employed. An injection is made with the delay circuit set to inject early in systole. If the maximum deflection from the radial artery is larger than that from the femoral, the catheter tip has entered the left subclavian artery. The catheter is then withdrawn and further injections made until a point is reached where visual observation of the galvanometer deflections appear to be approximately equal at the two recording sites. At this point the catheter tip must lie at or very near the origin of the left subclavian artery ($b = 0$). Also at this point, timing of the injection should not influence *R*. As the catheter is withdrawn measured distances thru the needle, (usually 3 to 5 cm. at a time) injections are made at each site at specified times in the heart cycle, making it possible to obtain *R* as a function of distance (b) and time. Measurement of the area of the recorded dye curves was simplified by the use of the triangle method.[6] If the sensitivity of the two dye detecting circuits is made the same, calibration is not necessary. Further, the amount injected need not be quantitated since *R* is independent of this parameter.

RESULTS

In figure 3 are shown recordings of dye concentration in arterial blood with time made following the injection of 0.62 ml. dye 0.2 sec. after the R wave of the electrocardiogram at various sites as the catheter was withdrawn down the aorta. *R* is measured as the ratio of the area under the radial curve to the area under the femoral curve at each injection site. The logarithm of *R* is plotted as a function of the distance in centimeters that the catheter is withdrawn. In most cases of aortic insufficiency the slope of such a plot can be represented by a constant (k) for values of *R* between 1.0 and 0.1. The constant k is the fractional decrease in *R* per centimeter withdrawn. In the absence of aortic insufficiency k is greater than 1.0, while in patients with clinically severe aortic insufficiency and dogs with one leaflet of the aortic valve incised to the ring, k is less than 0.2 (20 per cent decrease in *R* per centimeter). The most nearly constant k values are obtained when a delay of 0.4 sec. from the R wave of the electrocardiogram is used.

Figure 4 shows a plot of back-velocity (v) as a function of time calculated from the equation $v = \frac{1}{kRt_l}$ (see appendix). To obtain this data the injection time (t_l) was made to extend over the duration of diastole and *R* was varied as a function of distance. The integral of the back-velocity curve with time is distance and gives a maximum value of 29.5 cm. which checks well with the fact that the catheter could be withdrawn 25 cm. from the origin of the subclavian without R going to zero in this patient.

That the back-velocity plot does not always have the single-peaked contour just described is illustrated by another patient in figure 5 which shows a plot of R as a function of time when b equals 6 cm. The length and horizontal position of the lines represent the timing of the injections. The α fractions of the injection periods are equal to the corresponding values of R. If flow were forward only during systole and backward all during diastole (see fig. 1) all the α fractions would be expected to fall within a single time band (shaded area). In this case as well as in several others, a second band is present late in diastole. This is interpreted to mean that a surge of forward flow occurred in mid-diastole which separated two periods of backflow.

Discussion

Quantitation of the severity of the hemodynamic defect in a patient with aortic insufficiency may be accomplished simply by determining k, the fractional decay of R per centimeter at a delay of 0.4 sec. For example, when $k = 0.2$, b will be 11 cm. for $R = 0.1$. When $k = 0.1$, b will be 23 cm. for $R = 0.1$. If it is assumed that the average cross sectional area of the aorta in such a case is 4.0 cm.^{2} the "back volume per stroke" from this section of the arterial bed alone would be 92 ml.

The application of this technic to the location and quantitation of aorta-to-pulmonary-artery shunts is being studied. The dynamics of dye distribution associated with a communication at the level of the ascending aorta are similar to those of aortic insufficiency in most respects. If the shunt is from the descending aorta, no dye appears at the radial cuvette on the first circulation, since the backflow is into the pulmonary artery and dye does not get back to the origin of the subclavian.

Summary

A method has been described involving the measurement of the time-course of dye concentration of left radial and femoral artery blood following injection into the descending aorta at various points in time and space. This allows the calculation of the time-course of backflow-velocity in this segment of the arterial bed in patients with aortic insufficiency. Data has been presented which sheds some light on the hemodynamic pattern associated with this valvular defect. The simple measurement of k, the fractional decay of R per centimeter in one phase of the heart cycle, has served as a practical objective index to the severity of aortic insufficiency.

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Summario in Interlingua

Es describite un methodo measurante le propagation temporo-spatial del concentration del colorante in sanguine del arterias radial e femoral sinistre post su injection in le aorta descendente a varie punctos de tempore e de spatio. Isto permitte le calculation del propagation temporo-spatial correspondente al velocitate del fluxo retrograde in iste segmento del vasculatura arterial in patientes con insufficientia aortic. Es presentate datos que servi a elucidar le hemodynamismo que es associate con le mentionate defecto valvular. Le simple mesura de k, le declination fractional de R per cm in un phase del cyclo cardiac, ha servite como un practic indice objective del grado de severitate del insufficientia aortic.

References

1. Cournand, A.: Measurement of cardiac output in man using right heart catheterization: Description of technic, discussion of validity and of place in study of circulation. Fed. Proc. **4**: 207, 1945.
2. Gorlin, R. and Gorlin, S. G.: Hydraulic formula for calculation of the area of the stenotic valve, other cardiac valves and central circulatory shunts. Am. Heart J. **41**: 1, 1951.

3. FISHER, D. L.: The use of pressure recordings obtained at transthoracic left heart catheterization in the diagnosis of valvular heart disease. J. Thoracic Surg. **30**: 379, 1955.
4. NICKOLSON, J. W., IV AND WOOD, E. H.: Estimation of cardiac output and Evans blue space in man using an oximeter. J. Lab. & Clin. Med. **28**: 588, 1951.
5. WIEDERHIELM, C.: Amplifier for linear recording of oxygen saturation and dye dilution curves. Circulation Research **4**: 450, 1956.
6. WARNER, H. R. AND WOOD, E. H.: Simplified calculation of cardiac output from dye dilution curves recorded by oximeter. J. Appl. Physiol. **5**: 111, 1952.

APPENDIX

Derivation of $R = \alpha$

Definitions:

R, $\dfrac{\text{Area under radial dye curve}}{\text{Area under femoral dye curve}}$; F_s, flow in subclavian artery; F_a, flow in descending thoracic aorta; A, total amount of dye injected; A_s, amount dye entering subclavian; A_a, amount of dye in descending aorta; α, fraction of injected dye which gets back proximal to the origin of the left subclavian artery; β, $1-\alpha$.

From the standard equation for flow

$$F = \frac{A}{\int c \; dt} = \frac{A}{area} \qquad (1)$$

it follows that

$$\frac{A_s}{A_a} = \frac{F_s \; area \; radial}{F_a \; area \; femoral} = \frac{F_s}{F_a} R \qquad (2)$$

The amount of dye entering the descending aorta will be

$$A_a = \beta A + \alpha A - \gamma\alpha A - \Delta\alpha A \qquad (3)$$

where γ is the fraction of αA entering the subclavian. and Δ is the fraction of αA entering other branches of the aorta proximal to the left subclavian. If dye is distributed in proportion to flow,

$$\gamma = \frac{F_s}{F_s + F_a} \qquad (4)$$

Thus from equation 2, 3, and 4 it follows that

$$\frac{A_s}{A_a} = \frac{\gamma\alpha A}{\beta A + \alpha A\,(1-\gamma-\Delta)} = \frac{F_s}{F_a} R \qquad (5)$$

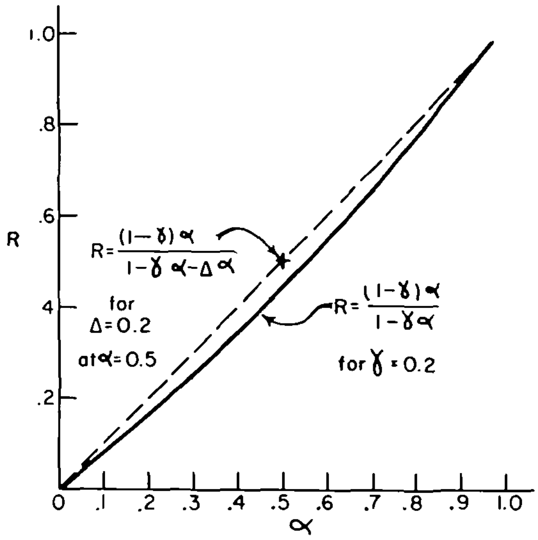

FIG. 6. Relationship between R and α calculated *from the equations shown. Broken line, line of identity.* See appendix for explanation.

Rearranging and solving for R yields

$$R = \frac{\left(\frac{F_a}{F_s}\;\frac{F_s}{F_s+F_a}\right)\alpha}{1-\alpha+\alpha-\gamma\alpha-\Delta\alpha} = \frac{(1-\gamma)\,\alpha}{1-\gamma\alpha-\Delta\alpha} \qquad (6)$$

During the course of an experiment γ is considered a constant. However, Δ depends essentially on α. The solid line in figure 6 is a plot of R vs α calculated from equation 6 assuming a value for γ of 0.2 and ignoring Δ, while the broken line is the line of identity. As α becomes large Δ becomes large, but has little effect on R since the Δ fraction at large value of Δ will diminish A_s and A_a approximately equally and R is independent of A. R calculated from equation 6 falls on the line of identity if a value for Δ of 0.2 is assumed at the point where $\alpha = 0.5$. That R will equal α to a good approximation over the whole range is supported by data such as that shown in figure 5 in which the R or α fractions of the injection periods fall nicely within well-delineated time bands.

Derivation of Velocity Equation

It has been shown that

$$R = f(x,t) \qquad (7)$$

where x is distance down the aorta in centimeters and t is time in seconds. On differentiating $ln\ R$ with respect to t, one obtains

$$\frac{d\,ln\,R}{dt} = \frac{\partial\,ln\,R}{\partial\,x}\,\frac{dx}{dt} + \frac{\partial\,ln\,R}{\partial\,t}$$

It has been found from experiment that

$$\frac{\partial \ln R}{\partial x} = -K \qquad (9)$$

over the range of values for R between 1.0 and 0.1. Since a given value of R can be obtained for any number of combinations of values for x and t,

$$\frac{d \ln R}{dt} = 0 \qquad (10)$$

and equation 8 becomes,

$$0 = -K \frac{dx}{dt} + \frac{\partial \ln R}{\partial t} \qquad (11)$$

or

$$\frac{dx}{dt} = \frac{1}{K} \frac{\partial \ln R}{\partial t} \approx \frac{1}{K} \frac{\partial \ln \alpha}{\partial t} \qquad (12)$$

since $R \approx \alpha$.

If the injection rate is constant, α is a fraction of injection time (t_1), and ∂t may be expressed as $t_1 \partial \alpha$. Thus, the back-velocity of the column of blood in the descending aorta is given by

$$\frac{dx}{dt} = \frac{1}{K\, t_1} \frac{\partial \ln \alpha}{\partial \alpha} = \frac{1}{K\, t_1\, R} \text{ cm./sec.} \qquad (13)$$

for values of R between 1.0 and 0.1

Thus by adjusting the time of onset and duration of injection (t_1) to correspond to diastole and measuring R at various points as the catheter is withdrawn, the instantaneous back-velocity at points corresponding to Rt_1 seconds after the onset of injection may be obtained. K is readily obtained from the relationship

$$K = \frac{2.3}{x_2 - x_1} \log \frac{R_1}{R_2} \qquad (14)$$

where R_1 and R_2 correspond to positions x_1 and x_2 measured in centimeters.