An Angiocardioangiographic Sign of Aortic Regurgitation
Its Utilization for the Measurement of Regurgitant Flow

By Rene A. Arcilla, M.D., Magnus H. Agustsson, M.D., Zwi Steiger, M.D., and Benjamin M. Gasul, M.D.

FOLLOWING the recent advances in cardiovascular surgery, the quantitation of abnormal hemodynamics has assumed paramount importance to clinicians and surgeons alike, and has been a constant challenge to research workers. The quantitative estimation of the severity of aortic insufficiency, for example, is still an unsolved problem. The different dye-indicator studies\(^1\)-\(^6\) and the technic of venous occlusion plethysmography introduced by Mackay\(^7\) are examples of efforts to solve this problem.

We wish to describe a technic of retrograde aortography done on five patients with aortic insufficiency and on five patients without this valvular defect. The aortograms demonstrate the movements of the opacified column of blood in the aorta, forward with ventricular systole and backward with diastole. While this phenomenon is a well-known hemodynamic assumption, it has not been demonstrated previously by contrast radiography. This paper deals with a description of the aortograms and their hemodynamic significance and with a presentation of a method for the estimation of the volume of regurgitant flow.

Materials and Methods

Ten patients were studied in this series; seven male and three female, and their ages ranged between 3 months and 19 years. Five had clinical findings of aortic insufficiency consisting of a wide pulse pressure, a hyperdynamic apical impulse, an accentuated aortic closure sound, and an early decrescendo blowing diastolic murmur over the aortic and left lower parasternal areas. The chest roentgenograms and electrocardiograms demonstrated left ventricular hypertrophy. The brachial arterial pulse tracings also showed the usual findings of aortic insufficiency. Two cases had associated mitral regurgitation, whereas the rest had isolated aortic insufficiency. The etiology of the valvular lesions was rheumatic fever. None of the patients was in congestive heart failure.

Retrograde aortography was performed on each of the 10 patients. In the five patients without clinical and laboratory evidence of aortic insufficiency it was performed to investigate some other extracardiac disorder. The method consisted of inserting a Lehman catheter of the widest diameter possible through an arteriotomy in the left brachial artery. The catheter was advanced under fluoroscopic guidance until its tip was in the descending aorta at least two inches below the arch. Ninety per cent aqueous solution of Hypaque sodium was injected rapidly in a dose of 0.7 to 1.0 ml per Kg of body weight. At the end of the procedure, the arteriotomy was repaired.

The angiocardiograms were obtained by means of an Elema angiocardiographic apparatus with an exposure time of 1/30 or 1/60 second, 8 radiograms per second being taken simultaneously in two planes. These were analyzed in detail, with special attention to the changing position of the opacified column of blood and to the diameter of the aorta during the various phases of the cardiac cycle. The stroke volume and the amount of aortic regurgitation were also calculated. In order to derive the actual size of the aorta from its apparent size in the aortogram, a standard correction curve for the magnification in the angiocardiogram was prepared from a plot of the per cent magnification of metallic rings of varying sizes at varying distances from the film and with a constant tube-to-film distance of 36 inches (fig. 1). These observations were made in both planes of the Elema angiocardiographic apparatus. Of the many factors producing image amplification, the object-to-film distance is practically the only one that needed correction in our study, since the angiocardiographic apparatus used had a fixed focal aperture, a fixed focal-film distance of 36 inches, and a fixed position and angulation of the tube in reference to the film.

The angiocardiograms were performed with the patient in the recumbent position. In every case, just prior to the injection of the contrast sub-


Figure 1

Relationship of angiocardiographic image magnification (expressed as per cent of the actual object size) to the object-to-film distance.

stance, the anteroposterior and transverse diameters of the chest and the distance of the midsternum from the lateral grid were accurately measured (fig. 2). The sagittal and transverse diameters of the chest in the aortograms were similarly measured. The distance from the midpoint of the descending aorta to the lateral chest wall (h) and to the posterior chest wall (l) were also determined from the aortograms. The true aorta-film distances in the anteroposterior and in the lateral planes were derived* and radiographic magnification of the aorta in either plane was determined from the standard correction curve (fig. 1).

Results

Aortographic Findings

The abnormal pulsatile flow in aortic insufficiency is clearly demonstrated in the aortogram (fig. 3). The opacified column of

\*To determine the aorta-to-film distance (fig. 2).

(a) In anteroposterior projection

\[ O_a = \frac{I}{C'D'} \cdot CD \]

\[ O_l = O_a + y \]

(b) In lateral projection

\[ O_t = \left( \frac{h}{A'B'} \cdot AB \right) + g \]

\[ O_r = O_t + y \]

\( O_a = \) aorta-to-grid distance in anteroposterior projection

\( O_t = \) aorta-to-film distance

\( O_r = \) aorta-to-grid distance in lateral projection

\( O_l = \) aorta-to-film distance

Figure 2

Landmarks in the chest and in the aortograms for deriving the true aorta-to-film distance. One grid is adjacent to the left chest wall and the other is under the patient's back. AB, lateral diameter of chest; CD, anteroposterior diameter of chest; A'B', lateral diameter of chest in the frontal aortogram; C'D', anteroposterior diameter of chest in the lateral aortogram; EF, distance from midsternum to grid; G, distance from left chest wall to grid; Y, distance from grid to film (constant); h, distance from descending aorta to left lateral chest wall in the frontal aortogram; l, distance from descending aorta to posterior chest wall in the lateral aortogram.

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Table 1

Data on Estimated Stroke Volume and Regurgitant Volume on Five Patients with Aortic Insufficiency

<table>
<thead>
<tr>
<th>Patient</th>
<th>Valvular defect*</th>
<th>Age (yrs.)</th>
<th>BSA (M²)</th>
<th>Diameter of aorta (cm) S-D</th>
<th>Stroke volume (SV) (ml/M²).²</th>
<th>Regurgitant volume (RV) (ml/M²).²</th>
<th>RV SV% 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AR</td>
<td>12</td>
<td>1.30</td>
<td>1.7</td>
<td>1.3 x 100 31%</td>
<td>.42</td>
<td>29</td>
</tr>
<tr>
<td>2</td>
<td>AR</td>
<td>19</td>
<td>1.75</td>
<td>2.6</td>
<td>1.9 x 100 37%</td>
<td>.54</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>AR</td>
<td>11</td>
<td>1.35</td>
<td>1.9</td>
<td>1.5 x 100 27%</td>
<td>.50</td>
<td>32</td>
</tr>
<tr>
<td>4</td>
<td>AR; MR</td>
<td>9</td>
<td>1.10</td>
<td>1.7</td>
<td>1.5 x 100 13%</td>
<td>.37</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>AR; MR</td>
<td>17</td>
<td>1.40</td>
<td>2.3</td>
<td>2.0 x 100 15%</td>
<td>.54</td>
<td>33</td>
</tr>
</tbody>
</table>

*AR, aortic regurgitation; MR, mitral regurgitation.
†Maximal diameter.
‡Minimal diameter.

Blood moves distally during ventricular systole and backward during ventricular diastole, the extent of the movements being indicated by the changing position of the peripheral zone of the contrast substance. This to-and-fro movement of the opacified column of blood is noticeable at the proximal portion of the descending arch and of the arch during several cardiac cycles. The aortogram also demonstrates the abnormal expansile movements of the aorta. Dilatation of the aorta occurs immediately during the early phase of ventricular systole (fig. 3A and 3F), followed later by a striking reduction in its size with the centripetal movement of the radiopaque material during diastole (fig. 3C to 3E).

In the other 5 patients without evidence of aortic insufficiency, the centripetal movement of the opacified column of blood during diastole was not observed. The differences in the aortic diameters during systole and during diastole expressed by the fraction,

\[
\frac{\text{diameter systole}-\text{diameter diastole}}{\text{diameter diastole}}
\]

were also not so much as in those with aortic insufficiency. The higher values noted in the latter group obviously reflected the greater stroke volume and also the considerable reduction in the aortic diameter during diastole as a result of the aortic reflux into the left ventricle.

Estimation of Stroke Volume and Regurgitant Volume

The forward movement of blood in any segment of the aorta during systole is due to the thrust imparted on the residual contents in the ascending aorta by the ventricular stroke volume. The extent of this forward displacement in any segment of the descending aorta indirectly indicates the stroke volume that has bypassed the brachiocephalic vessels. In aortic insufficiency the extent of the centripetal movement of blood in the arch and descending aorta similarly reflects the volume of regurgitation from the descending aorta into the left ventricle during diastole.

With our method the stroke volume is determined from the volume of the displaced contrast material following systole; the regurgitant volume is derived from the magnitude of the centripetal return of the opacified blood during diastole. The accuracy of the estimated stroke volume and regurgitant volume depends on how clearly defined these forward and centripetal movements are depicted in the aortogram. This, in turn, depends on how clearly outlined is the zone of demarcation between the dye-containing and the non-dye-containing blood columns in the aorta.

The difficulty in calculating the volume of any segment of the aorta, as seen in the aortograms, may be resolved by assuming that the aorta is a long, imperfect cylinder with its distal end smaller than its proximal portion in a gradually tapering fashion. Its proximal segment is arched, whereas its distal segment is straight (fig. 4). With a planimeter the surface area of any portion of the aorta in the aortogram can be measured.
Figure 3
Aortogram in case 1 demonstrating the to-and-fro movement of the opacified vascular column and the prominent expansile movements of the aorta. A, B, and C demonstrate the foremost movement of the column during systole; C, D, and E demonstrate the backward movement of the same column of blood during diastole. F illustrates the sudden increase in the aortic diameter with the onset of systole. Arrows indicate the approximate level of the contrast substance.
By dividing this area by the average diameter of the segment, the length of a rectangle with the same surface area is obtained. From the average diameter of the aortic segment, the mean circular area of the aorta is also derived. By multiplying this area by the "corrected" length of the aortic segment, (which is equivalent to the length of the theoretical rectangle), the volume of the aortic segment is obtained.*

\*To determine the volume of an aortic segment (fig. 4).

(a) Average diameter of aortic segment \( (D_a) \)

\[
D_a = \frac{D_1 + D_2 + D_3 + D_4 + D_n}{4 + n}
\]

(b) "Corrected" length of aortic segment \( (L_a) \)

\[
L_a = L_n = \frac{L_n}{D_a (or W_b)}
\]

(c) Volume of aortic segment \( (V_a) \)

\[
V_a = \pi r^2 l
\]

in which \( V \) = volume of any cylinder
in which \( r \) = radius of cylinder
in which \( l \) = length of cylinder

This equation may be used to determine volume of any aortic segment:

\[
V_a = \pi \left( \frac{D_a}{r} \right)^2 \cdot L_a
= 0.7854 \cdot D_a^2 \cdot L_a
\]

Figure 4

Diagram of a segment of the ascending aorta and descending aorta whose area is equivalent to that of the rectangle on the right. The arched segment \( (A) \) represents the ascending aorta; \( D_A, D_b, D_2, D_3, D_n = \) diameters of aorta at various levels; \( D_A = \) average diameter of aorta at segment; \( A_a = \) area of aortic segment; \( A_b = \) area of rectangle; \( L_b = \) length of rectangle; \( W_b = \) width of rectangle.

As demonstrated in figure 5, the distal border of the stroke volume at the end of ventricular systole would assume a lower level...
Diagram of the ascending and descending aorta illustrating the effect of aortic expansion on the distal level of the stroke volume ($S$). In diastole when the aortic diameter is narrower (dotted lines), the inferior level of an equivalent volume would be more distal ($D$). Thus the additional volume of the aorta ($\Delta V$) resulting from its dilatation during systole is equivalent to the volume of the descending aorta during diastole ($\Delta V'$) confined between the distal level of the stroke volume during diastole ($S$) and that of a similar volume during diastole ($D$).

if this volume were accommodated in the same aortic segment during diastole when its diameter is narrower. These two levels, the actual and the theoretical "diastolic" levels, demarcate a segment of the descending aorta ($\Delta a'$) whose volume during diastole is equal to the additional volume of expansion of the aorta during ventricular systole ($\Delta a$). This volume between the two levels is, therefore, equivalent to the value obtained by multiplying the stroke volume by the per cent of aortic dilatation during systole ($S - D \times 100 = \frac{\Delta V}{D}$).

Discussion

Since Corrigan’s original description of the characteristic bounding pulse in aortic insufficiency, numerous studies on the circulatory hemodynamics in this entity have been reported. Retrograde aortography performed with the injection of the contrast substance into the ascending aorta has been described by Wilder et al. They have shown that aortic reflux into the left ventricle occurs only when aortic insufficiency is present. While this method clearly demonstrates the regurgitant stream, it cannot quantitate the amount of aortic regurgitation.

The movements of the opacified column

$\Delta V = V_s + V_r$
of blood in the aorta, as demonstrated in our aortograms, confirm the well-established abnormal pulsatile flow in aortic insufficiency derived from studies on central and peripheral pressure pulse curves, electrokymograms, ballistocardiograms, and recently from indicator-dilution methods.\textsuperscript{1-6} The aortograms also demonstrate why effective systemic circulation time may be unusually prolonged, especially when the regurgitant volume closely approximates the stroke volume. In this condition a large portion of the systolic output remains in the proximal aorta for a longer time, because of its to-and-fro movement during ventricular systole and diastole.

The striking diminution in the diameter of the aorta simultaneously with the centripetal movement of the blood column refutes Stewart's original concept that the reflux volume in aortic insufficiency is small, and that the collapse of the pulse is due to reflex vasodilatation of the systemic vessels.\textsuperscript{10} Rather, it illustrates Wigger's contention, which is well accepted today, that the abnormal fall in the diastolic pressure is due to the regurgitation.\textsuperscript{11} These abnormal expansile movements of the aorta illustrate the typical water-hammer pulse in this entity. We do not need to take into account the possible influence of atherosclerosis on aortic distensibility in our group of patients.

The volume of regurgitation in aortic insufficiency has long been a matter of speculation. Stewart\textsuperscript{10} and later Wiggers and Green\textsuperscript{12} assumed only a small regurgitant volume; Lewis and Drury\textsuperscript{13} believed that as much as 50 per cent of the stroke volume may be lost in the regurgitant flow. Other investigators\textsuperscript{1-5, 14, 15} have suggested that the regurgitant volume may be equal to, or may even exceed the stroke volume. Although flowmeters have been successfully utilized in experimental studies, their clinical use in man is not feasible. The dye-dilution technics described by Warner and Toronto\textsuperscript{2} and by Braunwald and Morrow\textsuperscript{1} are based on the same principle. They consist essentially of injecting a dye-indicator substance at various levels of the descending aorta and simultaneously deter-

mining the dye concentration in the femoral artery and left radial artery,\textsuperscript{2} or in the right ear lobe by means of continuously recording oximeters.\textsuperscript{1} In the absence of aortic insufficiency, the dye is not detected in the radial artery or at the ear lobe during its primary circulation as long as the site of injection is below the level of the arch. In aortic insufficiency the lowest level in the descending aorta, from which the indicator substance is recovered into the brachiocephalic vessels, represents the inferior level of the blood column that returns centrally into the arch or ascending aorta during diastole. With varying degrees of aortic regurgitation, these levels also vary. The volume of aortic regurgitation that represents a fraction of the total aortic compartment is derived from the estimated total aortic volume. The indicator-dilution methods described by Korner and Shillingford\textsuperscript{3, 4} and by Lange and Hecht\textsuperscript{5} determine the ratio of the regurgitant to the nonregurgitant flow from the simultaneous pulmonary artery and systemic artery dye curves following peripheral venous injection of dye. The other method reported by Brotmacher et al.\textsuperscript{6} involves the injection of a dye into the ascending aorta, and recording simultaneous dye curves obtained from the left ventricle and from the femoral artery.

Our technic of retrograde aortography was designed basically on the same principle as the previous two dye-dilution methods.\textsuperscript{1, 2} It also involves calculating the volume of the aortic segment that the radiopaque substance traverses as it returns centrally to the arch or ascending aorta during diastole. It has the advantage of permitting the determination of the physiologic size and volume of the aorta at the time of the test. It also makes possible the estimation of the left ventricular stroke output, so that the degree of aortic regurgitation can be expressed as a fraction of the stroke volume. This is more accurate than expressing the regurgitation volumetrically alone, since in the determination of both the stroke volume and the quantity of aortic regurgitation, the volume of blood passing through the brachiocephalic vessels is not
considered. Since both determinations are calculated by the same method, any error inherent in the method is reflected in both values.

The method is not devoid of difficulties and sources of error. The peripheral border or edge of the opacified column (see arrows, figs. 3 and 6) is not always distinctly outlined, especially at the beginning of systole when dispersal of the contrast material at the demarcation zone by forces other than those under study occurs. This difficulty is obviated if the contrast substance is injected rapidly into the descending aorta, for which reason the catheter with the widest diameter that can be accommodated in the exposed brachial artery is desirable. An arteriotomy is necessary that must be repaired at the end of the procedure. Since the aortograms are taken at a speed of 8 radiograms per second, the border of the contrast substance in late systole, as viewed in the film immediately preceding the picture demonstrating early centripetal movement, would not be at the same level were the picture taken at the end of systole. The same difficulty is encountered in determining the level of the contrast substance at the end of diastole. The identification of these nondiscernible vascular movements, which occur within the last 0.09 to 0.10 second (time interval between two successive frames) of systole and diastole, is obviously essential for more accurate estimation of the stroke volume and the regurgitant volume. Cineangiocardiography should eradicate this difficulty. On the other hand, the delineation of the borders of the contrast substance may not be so distinct as in the serial aortograms.
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Caution must be exercised in interpreting the movements of the opacified column of blood in the aortogram. As long as the contrast substance is still being injected, a false centripetal movement may be misdiagnosed in a normal aortogram. If the rate of blood flow is greater than the rate of injection of the contrast substance, the level of the radiopaque material moves farther distally from the site of injection during ventricular systole. With the onset of diastole, the incoming contrast substance accumulates at the area of injection, giving the false impression of a centripetal return of the opacified blood. A closer scrutiny, however, reveals that this "diastolic pseudomovement" is noted immediately at the onset of diastole, and does not show the gradual ascent of the radiopaque material characteristically seen in aortic regurgitation. The upper level of the contrast material also does not go appreciably higher than the level of the tip of the catheter. These phenomena are well demonstrated in figure 6a, which shows the serial levels of the contrast substance at systole and diastole during its injection and in figure 6b, after the injection is completed.

While this method represents another means for the physiologic evaluation of the degree of aortic regurgitation, it must be compared with other methods before its usefulness is fully established. We have not yet undertaken this comparative study. The use of both the dye-indicator technics and the present method

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Figure 6b
Aortograms of the same patient taken after the injection of the contrast substance is completed. The "pseudocentripetal" phenomenon is no longer observed and only a forward movement of the contrast substance exists (D, E, and F).
on the same patient would be ideal for this type of investigation.

**Summary**

A technic of performing retrograde aortography for the study of aortic insufficiency is presented. The aortograms demonstrate the abnormal expansile movements of the aorta, and the to-and-fro motion of the opacified vascular column in the proximal portion of the aorta with systole and diastole. These phenomena were not observed in patients without aortic insufficiency. A method for calculating the stroke volume and the volume of regurgitation from these aortograms is presented.

**References**

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13. **Lewis, T., and Drury, A. M.:** Circulatory manifestations on clinical cases with particular reference to the arterial phenomena of aortic regurgitation. Heart 10: 301, 1953.

A discovery is usually an unforeseen relation not confirmed in theory, for otherwise it would have been foreseen.—Claude Bernard
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