Ventricular Function

II. Quantitative Relationship between Coronary Flow and Ventricular Function with Observations on Unilateral Failure

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Left main coronary artery blood flow, cardiac output and pressures in the pulmonary artery, the aorta and both atria were continuously recorded in the dog. Restriction of left coronary flow increased left atrial pressure substantially, but right atrial pressure only slightly; left ventricular work, cardiac output and arterial pressure fell markedly. During restriction of left coronary flow, the left ventricular function curve (modified Starling curve), which does not normally show a descending limb even at high filling pressures, developed a pronounced descending limb. Unilateral ventricular failure was demonstrated.

A QUANTITATIVE measure of the full range of right and left ventricular function in the dog with a complete circulation was made possible by a recently developed technique. To this has been added the measurement of left main coronary artery flow so that the relationship between coronary flow and ventricular function could be quantitatively analyzed.

The objectives of this communication will be (a) to show the acute hemodynamic effects of restricting coronary flow, (b) to quantitate the relationship between coronary flow and ventricular performance by means of ventricular function curves (modified Starling curves), (c) to demonstrate that a descending limb on the ventricular function curve is not normally present but appears after coronary insufficiency is induced, and (d) to present data bearing on the question of unilateral ventricular failure.

METHOD

Under morphone-chloralose-urethane anesthesia, and with positive pressure breathing, ribs 3, 4 and 5 were resected on the left. The circulation was then rearranged according to the schematic diagram shown in figure 1. Blood leaving the left ventricle enters the aorta from which it flows through the Potter Electroturbinometer to the descending aorta and the brachiocephalic artery. Just before the entrance to the Electroturbinometer, a side arm leads a portion of the blood through a recording rotameter of the type described by Shipley and Wilson. From this, blood flows to a modified Gregg coronary cannula the tip of which is secured in the lumen of the left main coronary artery by a previously placed silk ligature. Thus, all the blood leaving the left ventricle is metered except that entering the right coronary artery which is approximately 15 per cent of total coronary flow. Pressures were measured in the left and right atria, and in the pulmonary artery and aortic arch by means of Electromanometers. All values were continuously recorded on a four-channel direct-writing oscillograph. Three values were recorded on one of these channels by means of the Sanborn Triplexer. Clotting was prevented with Treburon. The filling pressure of both ventricles was increased in a step-wise fashion by allowing a mixture of blood and Dextran to enter the right atrium or femoral vein from a reservoir. In this way data were gathered for the calculation of right and left ventricular function curves. In some experiments a bilateral high cervical vagotomy was performed.

Ventricular stroke work was calculated by multiplying stroke volume by the difference between mean arterial and mean atrial pressure. Right and left ventricular function curves were obtained by plotting the stroke work of each ventricle against...
Coronary Flow and Ventricular Function

Fig. 1. Schematic drawing of the techniques used for measuring flows. PET = Potter Electroturbinometer; ROT = rotameter; CT = coronary tubing; LS = left subclavian artery; B = brachiocephalic artery; A = aorta; GCC = Gregg coronary cannula; LMCA = left main coronary artery; LA = left atrium; LV = left ventricle. PET measures cardiac output minus coronary artery flow. ROT measures total left main coronary artery flow. The sum of the flows through PET and ROT = cardiac output minus right coronary artery flow.

Results

Two types of results are presented from the eleven dogs in which a successful preparation was achieved. The first are acute hemodynamic changes resulting from the restriction of coronary flow. The second are ventricular function curves before, during and after the release of varying degrees of coronary constriction.

1. Hemodynamic Changes Occurring after the Restriction of Coronary Flow. Figure 2 (A to D) shows the changes in left coronary flow, cardiac output, right and left atrial and pulmonary and aortic pressures resulting from constriction of the tubing which supplied the left main coronary artery. Also shown are the calculated values for right and left ventricular stroke work. Of interest is the progressive fall of its mean atrial pressure over the whole range of atrial pressures obtained.

Fig. 2. Serial sections of a tracing showing the results of restriction of left main coronary artery flow. Experiment 93. Dog weight 26.0 Kg. Heart weight 178 Gm. Pericardium open. Vagotomy. Screw-clamp was applied after A and released just before D. PA = pulmonary artery mean pressure, scale at the left; LA = left atrial mean pressure; scale at the right; RA = right atrial mean pressure, scale at the left; LCF = left main coronary artery flow; RV = right ventricle; LV = left ventricle; stroke work in gram meters; system flow = cardiac output minus coronary flow. Time, 1 second. Note the substantial rise in LA with almost no rise in RA; also myocardial reactive hyperemia in F.
cardiac output, aortic pressure and coronary flow, the appearance of pulsus alternans and no change in pulse rate. Accompanying this there is a marked rise in left atrial pressure, whereas right atrial pressure increases only slightly. The clamp constricting the coronary artery was released just before D, with a subsequent slow return of the values to or near control levels at G. The marked decrease in stroke work of the left ventricle occurred despite a rising left atrial pressure. While right atrial pressure rose only slightly (from 3.3 to 3.9 cm. H₂O) left atrial pressure increased substantially (from 9.3 to 23.2 cm. H₂O).

Reactive hyperemia of the myocardium following ischemia has been previously demonstrated by Katz, among others. It is also clearly shown in this experiment. Left coronary flow, after falling from its control value of 132 to a low point of 22 cc. per minute, rose following release of the clamp to 170 cc. per minute and 10 minutes later was at its control value.

In one experiment of the same type in which coronary sinus blood was sampled, the coronary A-V oxygen difference rose from 10.6 volumes per cent during the control state to 13.8 volumes per cent during the period of restricted coronary flow.

With the method described it was not possible to control completely the blood supply to each ventricle; inasmuch as the left coronary artery supplies a significant portion of the right ventricle. However, it is clear that with this severe restriction of the left main coronary artery flow, the left ventricle was compromised to a considerably greater extent than the right as evidenced by their changes in filling pressures and stroke work.

In two experiments the right coronary artery was completely occluded. In one of these the result was a rise of right atrial pressure with a fall in right ventricular stroke work; in the other there was no change.

2. Depression of Ventricular Function Curves by Graded Restriction of Left Main Coronary

![Fig. 3. Right and left ventricular function curves.](image-url)
Flow. Figure 3 shows ventricular function curves for both the right and left ventricles. Left main coronary artery flow, aortic pressure, and stroke volume are also shown plotted against left atrial pressure. Pulmonary artery pressure and stroke volume are plotted against mean right atrial pressure. The dots represent values obtained in the control run. The X's represent values obtained after "mild" restriction of left main coronary flow and the triangles after "moderate" restriction. The coronary tubing screw-clamp was then removed and a second set of control values obtained as indicated by the circles. The return of the ventricular function curve to its control level after removal of the coronary screw-clamp indicates that the depression of the ventricular function curves during the stenosis was not due to failure of the preparation.

There are several aspects of the data shown in figure 3 worthy of comment: (a) The control curves on the left rise steeply and then flatten to a plateau. A descending slope is not seen even out as far as 48 cm. H_2O. (b) A restriction of left main coronary artery flow depresses the left ventricular function curve and the degree of this depression varies with the degree of coronary flow restriction. (c) A descending limb on the left ventricular function curve appears only after coronary insufficiency is produced and disappears when the latter is relieved. (d) The depression of ventricular function (failure) can be unilateral. (e) The plot of right atrial pressure against stroke volume (lower right part of figure 3) gives the erroneous impression that right ventricular function is seriously depressed and shows a descending limb following moderate restriction of left coronary flow. That this is not the case is apparent from the plot of right atrial pressure against stroke work which demonstrates that right ventricular performance was unaffected by restriction of left main coronary artery flow. That is to say, the right ventricle still produced as much stroke work per unit of filling pressure, but this was composed of more pressure work and less output work.

![Diagram](http://circres.ahajournals.org/)

**Fig. 4.** Right and left ventricular function curves. Experiment 43. Dog weight 18.4 Kg. Heart weight 140 Gm. Vagotomy. Dots and circles = control curves. Triangles = curves during mild restriction of coronary artery flow. Crosses = curves during severe restriction of coronary flow. Discussion in text.
Figure 4 presents data similar to that seen in 3, and in addition shows one set of curves (x's) during which restriction of left coronary artery flow was severe. Under these circumstances the right ventricle as well as the left exhibited a depressed function curve. During this curve, however, aortic pressures were very low, and it may be assumed that the right as well as the left coronary flow was inadequate.

An analysis of 44 simultaneous right and left ventricular function curves obtained in nine dogs yielded results similar to those shown above.

In two experiments ventricular function curves were plotted before, during and after complete occlusion of the right coronary artery. In one of these there was a slight depression of the right ventricular function curve; in the other there was no change.

3. Relation between Right and Left Atrial Pressures in Unilateral Failure. In figure 5 the simultaneous right and left atrial pressures obtained from the control run and the coronary constriction runs of the experiment shown in figure 3 are plotted against each other. There is a shift of the curve to the left when coronary artery flow is restricted, and a return to the control curve after removal of the stenosis. This is another indication, as pointed out by Berglund and colleagues, that the left atrium/right atrium pressure relationship depends chiefly upon the functional state of the two ventricles rather than upon the distensibility of the atria.

DISCUSSION

The preparation used in this study makes possible an analysis of the physical factors determining the performance of each ventricle, and a comparison of the functional changes after a given intervention. In addition to quantitatively relating ventricular function to coronary flow, the changes resulting from a restricted coronary flow revealed a number of other noteworthy relationships.

The classic concept of Starling's law of the heart embodies a single curve with a sharp descending limb. This concept is largely responsible for the widespread feeling that myocardial failure represents a heart which is working on this descending limb. In contrast to this, it was recently demonstrated that without myocardial failure or regurgitation, the ventricular function curve rises to and maintains a plateau.

It is now abundantly clear that the normal heart does not exhibit a descending limb on its ventricular function or Starling curves. Conversely, the appearance of a descending limb can be brought about by compromising the metabolic support of the myocardium. The descending limb that is so frequently obtained in the heart-lung preparation can be partially accounted for on this basis.

Depression of ventricular function due to coronary flow restriction was not always apparent at low filling pressures but was clearly revealed at higher filling pressures when the coronary flow requirement was higher (figure). This, among other things, reaffirms the authors' view that a full Starling or ventricular function curve is more likely to yield
fruitful information than isolated points, just as exercise may be necessary to reveal impaired function in the patient.

It is clear that the force with which the ventricle contracts is a function of its effective filling pressure (obeys Starling’s law) in the normally responding heart as well as during failure.\textsuperscript{12, 13}

These experiments also demonstrate (figure 4) that the relation of filling pressure and \textit{stroke volume} may give an erroneous impression. The data reaffirm the opinion of Starr and associates\textsuperscript{14} that stroke work is the most informative value to consider in the analysis of ventricular function. Some of those who question the validity of Starling’s law have attempted to correlate performance of the left ventricle with the filling pressure of the right, a method that might be acceptable if the two atrial pressures maintained a consistent relationship to each other. That this is not the case has been amply demonstrated here.

Although anatomically the muscle bundles of the two ventricles are in continuity to a large extent, and their beats are initiated by a common electrical impulse, they are functionally two separate pumps. For, as seen above, it was possible to preferentially compromise the performance of the left ventricle while leaving the right unaltered and thus demonstrate the occurrence of unilateral failure. These data confirm the studies of Lewis and co-workers.\textsuperscript{16} They found that when three of five patients in hypertensive failure were exercised, a rise in “pulmonary capillary” pressure was accompanied by a decrease in left ventricular stroke work. At the same time a rise in right atrial pressure produced a rise in right ventricular stroke work.

It would appear from the above that the elevation of right atrial or systemic venous pressure sometimes seen with myocardial infarction may depend not only on the severity of the infarction, but also the degree to which the right ventricle is involved.\textsuperscript{16}

\textbf{Summary and Conclusions}

Left main coronary artery flow, cardiac output, right and left atrial and pulmonary and aortic pressures were continuously recorded in the open-chested narcotized dog with a complete circulation. Forty-four right and left ventricular function curves (modified Starling curves) were obtained, and on the basis of these the following conclusions were reached.

Left ventricular function is quantitatively related to left main coronary artery blood flow.

Unilateral depression of left ventricular function (unilateral failure) can occur and is quantitatively related to coronary insufficiency.

The relationship between right and left atrial pressures depends primarily on the functional state of the right and left ventricles rather than on the distensibility of the atra.

The strength with which ventricles contract is a function of effective filling pressure (Starling’s law), not only in the failing heart but also in the normally responding heart in the dog with a complete circulation.

In the control ventricular function curve there was no descending limb, but the latter did appear during left ventricular failure due to coronary insufficiency.

In the analysis of the function of the ventricle itself, stroke work is a more informative value than stroke volume.

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9 --: Ventricular function. VI. The relationship between left and right atrial pressures and its role in maintaining an equal output from the two ventricles. Submitted for publication.


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Circ Res. 1954;2:319-325
doi: 10.1161/01.RES.2.4.319

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/2/4/319

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