Changes in Configuration of the Ventricular Chambers during the Cardiac Cycle

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Cinefluorographic angiocardiography has been used to record the sequential changes in the size and shape of the right and left ventricular chambers and the external cardiac silhouette in dogs. Evidence is presented which indicates that (1) the left ventricle is usually filled more rapidly than it is emptied, (2) the diastolic size appears to remain remarkably constant during a major portion of the diastolic period and (3) residual blood remains within the ventricle at the end of systole.

Cyclic changes in the size of the ventricles, the essential feature of cardiac function, have been widely studied by a variety of methods: (1) direct volumetric measurements by the plethysmographic technique, (2) analysis of arterial pulse waves, (3) roentgenkymography, (4) electrokymography and (5) indirect information concerning changes in stroke volume, gained from cardiac output determination by the Fick principle or ballistocardiography. The length of this list emphasizes the importance of information concerning the mechanism of ventricular contraction, and each method has certain advantages. Motion pictures of fluoroscopic images during angiocardiography present a combination of advantages not available in other methods. The size and the shape of the heart and of the individual chambers can be observed and measured during multiple cardiac cycles in the intact experimental animal. The presence of residual blood is readily detected in the ventricle. The sequence of events in the great vessels and heart can be related. Two disadvantages of this method are recognized: (1) the recorded images represent a two dimensional projection of the cavities, (2) rapid injection of radiopaque materials imposes an unusual load on the heart and circulation.

Methods

Cinefluorographic angiocardiography was performed on 20 dogs anesthetized with Nembutal and reclining in the left lateral position. The action was recorded with 16 mm. and 35 mm. cinefluorographic equipment.\(^1\)\(^2\)* Diodrast\(^\dagger\) (25 cc. of a 70 per cent solution) was rapidly injected through indwelling needles or catheters secured in a jugular vein. Cinefluorographic recordings for 10 and 14 seconds provided an uninterrupted cinematic record of the opacified blood passing from the superior vena cava, through the heart and lungs and into the aorta. Eight films were exposed at a rate of 30 frames per second; the remainder at 15 frames per second. Various methods were used to extract information from the motion picture films: (1) repeated examination using motion picture projectors, (2) study of action and individual frames on film editing devices, (3) tracings of the projected images from film sequences, (4) photographic enlargement of strips of film and (5) a special motion picture printing technic termed "counter-offset" printing,\(^3\) which is based on the following principle. In positive and negative copies of the original cinefluorographic film, the light areas in one correspond precisely with the dark areas in the other. If these two films are accurately superimposed in a printer, they partially neutralize or counteract each other, tending to produce a uniformly gray field. However, if the two counteracting films are superimposed with one film offset one frame in advance of the other, stationary structures remain subdued but the movement of a structure during the interval between frames appear as an area of markedly reduced density because in this area neutralization is less complete. Thus the time course of the move-

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ment of radiopaque material may be followed on successive frames. In figure 4, the first series of four pictures (A-1, 2, 3, 4) corresponds to an original negative film. The second series (B-1, 2, 3, 4) was obtained by counter-offset printing. Some structural detail is visible because the density and contrast of the two superimposed films are not identical. However, in each frame, the leading edge of the Diodrast column moved into the dark areas on each frame during one-fifteenth second.

RESULTS

Continuous cinefluorographic recording at 15 frames per second for 10 to 14 seconds produced 150 to 200 stages in the progression of the radiopaque substances from the superior vena cava to the descending aorta. The anatomic relations of the cardiac chambers in the dog are illustrated in Figure 1. The first portion (6.4 seconds) of a typical record is reproduced in figures 2 and 3. Diodrast approached and entered the right atrium during the eight frames in column A and the first five frames in column B (fig. 2). The auricular appendage was outlined between frames B-3 and B-7, the position of the tricuspid valves was clearly indicated in frames B-3, 4, 5, and retrograde flow into the azygos vein appeared in frames B-4, 5. In frame B-6 the tricuspid valves opened and opacified blood surged into the right ventricle. The first visible contraction of the right ventricle occurred between C-4 and C-8, filling the pulmonary arteries. Refilling of the right ventricle was largely complete within one-fifteenth second between C-8 and D-1. Retrograde flow into the inferior vena cava began during a diastolic period (D-3) (the next systole began in frame D-8). Since the diaphragm was rising at this time, the retrograde flow occurred during the expiratory phase of respiration, but this was not necessarily true in other cases. During the second right ventricular systole (D-8, E-1, 2, 3), Diodrast appeared in the left atrium only 1.3 seconds after initial right ventricular opacification. The systolic period occupied four frames (C-4, 5, 6, 7 and D-8, E-1, 2, 3) while filling of the chamber appeared complete within two frames (C-8, D-1, and E-4, 5). During the remainder of the diastolic period the right ventricular chamber was remarkably constant in size and shape even though the injection of Diodrast was forceful enough to produce retrograde flow for a considerable distance into the inferior vena cava. The left ventricular cavity became partially opacified during the final diastolic filling in figure 2 (frames F-7, 8).

During the next three seconds, both ventricles were simultaneously opacified by the Diodrast (fig. 3). The interatrial and interventricular septa can be identified, separating the right and left atria and the two ventricles respectively (fig. 3, J-1–7). Between the left atrium and left ventricle, the location of the mitral valve appears in a number of pictures, particularly H-5, 6, 7, 8, and K-5, 6, 7, 8. As the right ventricle became cleared of Diodrast, the left heart chambers could be more readily distinguished. The thoracic aorta could be followed from the aortic bulb to the descending limb of the arch (fig. 2, frames L, 1–8). The rapidity of early diastolic filling (L-1, 2) of the left ventricle relative to the systolic period (K-4–7) is also evident in this series.

*Right Ventricular Filling.* Right ventricular...
filling can best be studied during the initial entrance of Diodrast into that chamber. As the tricular chamber (A-4). The progress of the Diodrast during each one-fifteenth second in-
the right atrium filled with radiopaque material during systole, the tricuspid valves became outlined at the atrioventricular junction (fig. 4, A-2, 3). The tricuspid valves inverted slightly into the right ventricle (fig. 4, A-2, 3) and gaped wide as blood gushed into the ven-
terval is indicated by the dark areas in the counter-offset print (fig. 4, B-1, 2, 3, 4).
Currents of flow within the ventricular chamber were frequently observed. In 3 animals, Lipiodal, characterized by its cohesion and immiscibility with blood, was injected in lieu of
Diodrast. In each case, the stream of Lipiodal executed a spiral movement as it entered the right ventricular chamber (fig. 4 C, D, E).

Currents of blood, reflected back toward the tricuspid valve (fig. 4, E-2) were frequently observed, but in each case they occurred well before the end of the diastolic period.

Right Ventricular Contraction. The right ventricle resembles a triangular pocket attached to the left ventricle along the interventricular septum. Bounded by the free wall of the right

A similar spiral pattern of Diodrast was noted in one case. The inferior vena cava enters the right atrium near the point at which the spiral configuration began (note arrows in D-1 and E-1). The inflow of blood from two convergent sources may be responsible for the swirling motion imparted to the stream of Lipiodal.
ventricle and the bulging interventricular septum, the right ventricular chamber is concavo-convex (fig. 1). The distance between the septum and free wall is greatest along the inflow tract and becomes progressively less toward the periphery. When a low concentration of contrast media filled the chamber, the remarkably thin space between the opposing surfaces from the catheter to the central cavity and the pulmonary artery was rapidly filled (B-1). A branch of the pulmonary artery, filled with the same concentration of Diodrast that existed in the right ventricle, passed anteriorly over the heart shadow along a course roughly parallel to that of the catheter (fig. 5, B-1). It is apparent that the layer of blood in the periphery at the periphery of the ventricular cavity was readily penetrated by x-ray.

In one experiment, a rubber catheter, inserted through the right jugular vein into the right ventricle, outlined the lateral extent of the right ventricle (fig. 5). At the end of a diastolic period (fig. 5, A-2), Diodrast was fairly evenly distributed through the right ventricular chamber. During the succeeding systole (A-2, 3, 4 and B-1) compression of the lateral portions of the right ventricle cleared the region portion of the right ventricle is little if any thicker than the diameter of the small branch of the pulmonary artery. Even during diastole, the opacity of the pulmonary branch is as great as most of the peripheral areas (fig. 5, B-3, 4 and D-3, 4). The configuration of the central portion of the right ventricular chamber is illustrated by a counter-offset print (fig. 5, E-1–4) in which the peripheral portions of the chamber do not obscure the pictures. The first three frames (E-1, 2, 3) reveal the systolic

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**Fig. 4.** A. Inversion of the tricuspid valves and initial filling of the right ventricle. B. Counter-offset print of the sequence in A to emphasize the progress of the contrast media in each frame (see text). C. Spiral currents of flow within the right ventricle during diastole are indicated by a streamer of iodized oil (outlined by interrupted white lines). Catheters for recording right and left atrial pressures also appear in the pictures.
size and the final frame (E-4) records the initial stage of diastole.

**Left Ventricular Contraction.** Since the contrast medium was diluted in the lungs, opacification of the left ventricle was gradual and left ventricular filling could not be adequately studied. In one animal with relative bradycardia, one cardiac cycle occupied twenty-four frames (fig. 6, A-1 to F-4). The change in capacity of the left ventricular cavity from atrial systole (fig. 6, A-1) to complete filling (fig. 6, F-4) represents only a small fraction of its total content. A large residual volume remained at the end of systole (C-4).

The left ventricular chamber is irregular in shape but most closely approximates a cylinder with a short conoid segment extending from both ends (fig. 6). During left ventricular systole, a reduction in the capacity of the left ventricle could result from compression of the cross-sectional diameter, from shortening of the chamber, or both. Marked narrowing and slight shortening of the ventricular cavity produced an unusual degree of systolic emptying in one experiment (fig. 3, K-6, 7). In another animal, a large residual ventricular volume remained at the end of systole (fig. 6, C-4) since the diameter of the chamber was reduced to a lesser degree and there was no visible change in length. In every case, left ventricular systole was characterized by a marked reduction in width and a relatively insignificant degree of shortening.

The aorta characteristically became narrow

![Diagram](http://circ.ahajournals.org/DownloadedFrom)
during the diastolic run-off period, and the ascending limb of the aorta subtended a very acute angle with the long axis of the left ventricle (fig. 6, A-1). Left ventricular systole expanded the aorta (Fig. 6, C-1, D-1) while the angle between the ascending aorta and the left ventricle was increased (D-1). During projection this phenomenon produces a rocking motion of the ascending aorta which assumed a more nearly vertical position during each systole and inclined posteriorly during diastole. Rapid injection of blood from the ventricle apparently elongated the aorta elevating the arch. However, it is worth noting that, contrary to the principle of the Borden tube, the aortic arch assumed a greater curvature during periods when its luminal pressure was increased.

**DISCUSSION**

The observation that diastolic filling of the ventricles occurs at a very rapid rate is not new. Henderson in 1906 described plethysmographic recordings of the changes in ventricular volume as follows: "The rapidity of the inflow indicated by this rise of the volume curve is startling; for it shows that the refilling of the ventricles occurs early in diastole, and that it is as rapid a process as is the systolic emptying." He summarized the work of earlier investigators and pointed out that Luciani, obtaining similar records, had gone so far as to propose an active diastolic expanding force originating in the myocardium.

The retrograde flow of radiopaque material into the azygos and inferior vena cava is a consequence of the rapid injection of a fairly large quantity of fluid into the expandile venous system. The fact that retrograde flow into the inferior vena cava occurred while the apparent size of the right ventricle remained relatively constant supplies confirmatory evidence that, early in diastole, the chamber becomes rapidly filled to a point beyond which further distension is resisted by unknown factors. Since filling was virtually completed during the first third of a diastolic period at heart rates up to
180 per minute, the rate of diastolic filling is probably not the primary limiting factor in cardiac output produced by tachycardia under normal conditions. Stead and Warren,

1 reporting conditions under which changes in cardiac output occurred without corresponding changes in venous pressure, concluded that the venous pressure is normally more than adequate to produce ample filling of the ventricular chambers.

Judging by the cinefluorographic records, the configuration and contraction of the right and left ventricular chambers are very different. The right ventricle resembles a pocket fastened to the periphery of the convex intraventricular septum. During contraction, the free wall conforms more closely to the convex septum, ejecting blood into the pulmonary artery and at the same time evacuating most of the blood contained around the periphery of the chamber. The left ventricle resembles a cylinder with a conoid segment at the apical end. Systole produces primarily a reduction in the diameter of the chamber. Shortening of the ventricle plays a minor role in the systolic ejection. It is generally stated that during systole the heart is rotated on its long axis. If this were true, the septal shadow separating the two ventricles would tend to become obscured by the opacified blood. There was no evidence for rotation of the heart in any case studied. The elongation and elevation of the aortic arch during systole is probably an expression of some of the forces recorded by the ballistocardiogram.

Conclusions

1. Angiocardiograms, recorded cinefluorographically, characteristically revealed a retrograde flow of opacified blood into the azygos vein, the inferior vena cava and occasionally into the opposite jugular vein, presumably due to the rapid injection of 25 cc. of radiopaque material.

2. As the right ventricle filled, currents of flow were generally observed. Lipiodal, injected in lieu of Diodrast, executed a spiral movement as it entered the ventricular chamber. Streams of blood from the superior and inferior venae cavae converging from different directions may underlie this finding.

3. The filling of both right and left ventricles occurred more quickly than systolic ejection. The area of the ventricular chambers appeared to remain relatively constant during the last two-thirds of diastole, even in the presence of retrograde flow into the inferior vena cava. This observation has been confirmed by planimetric measurements which will be described in a subsequent report.

4. Left ventricular contraction involved primarily a reduction in the width or diameter of the chamber. Shortening of the long axis of the ventricle played a minor role in systolic ejection.

5. During systole, the diameter of the aorta was markedly increased and the aortic arch became elevated and more acutely curved.

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