Dependence of ventricular distensibility on filling of the opposite ventricle

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Taylor, Roger R., James W. Covell, Edmund H. Sonnenblick, and John Ross, Jr. Dependence of ventricular distensibility on filling of the opposite ventricle. Am. J. Physiol. 213(3): 711-718. 1967. The influence of filling one ventricle on distensibility of the opposite ventricle was examined in dogs. Distensibility of the left or right ventricle was consistently decreased in proportion to the filling of the opposite chamber. To quantify the effect of right ventricular (RV) filling on left ventricular (LV) distensibility in the intact circulation the coexisting LV and RV end-diastolic pressures (EDP) were determined over a wide range of ventricular filling induced by blood infusion. LV pressure-volume relations were then obtained in the arrested heart and each level of LV filling pressure was matched with the RV filling pressure found to coexist in vivo. The effect of RV filling on the LV volume when LVEDP was low (3 mm Hg) was not discernible. The effect was apparent when LVEDP was 5 mm Hg with the appropriate RV filling, the LV volume being decreased by 1.8 ± 1.2 (SD) ml. At an LVEDP of 20 mm Hg the reduction was 3.9 ± 2.4 ml or 7.1 ± 4.7% of LV volume; LV volume at an RV EDP of 20 mm Hg therefore was 7.1% smaller with the RV full than with the RV empty. This effect is considered to result from the sharing of a common septum and fiber bundles. The effect should be considered when the passive diastolic pressure-volume relation is compared with that in the beating heart and whenever ventricular function is examined over a range of cardiac filling pressures. It may also play an important role when either ventricle is acutely distended in disease states.

compliance; ventricular filling; pressure-volume relations; ventricular volume; Bernheim

RIGHT AND LEFT VENTRICLES of the mammalian heart are anatomically related by a common septum and by circular and spiral bundles of muscle fibers which encircle both ventricles (12, 16, 20, 22). Therefore, it might be anticipated that filling of one ventricle would affect the distensibility of the opposite chamber. That this is the case has been evidenced by the finding that the ventricles of the dog heart are more distensible when filled individually than when both are filled simultaneously with equal volumes (14, 25). Such a change in the relation between ventricular diastolic volume and pressure is clearly of importance in considering ventricular performance (10, 11, 91), and it could be especially relevant when alterations in the filling pressures of one or both ventricles are acutely induced, as in the determination of a ventricular function curve (2). However, there has been no systematic investigation of this problem, nor has its importance in the intact heart over a range of ventricular diastolic pressures been analyzed.

In the present study, coexisting left and right heart filling pressures were first determined in the beating heart over a wide range of ventricular filling pressures produced by blood infusion. The heart was then arrested in diastole in situ and the distensibility of each ventricle examined during variable filling of the opposite ventricle, particular attention being directed to the effect on the left ventricular pressure-volume relation of the physiologically appropriate degrees of right ventricular filling, i.e., those associated in vivo with the various levels of left ventricular filling.

METHODS

Eight dogs weighing between 14.5 and 24.0 kg were anesthetized with pentobarbital (30 mg/kg). Respiration was maintained with a Harvard respiratory pump, a bilateral thoracotomy was performed, and the heart was suspended in a pericardial cradle. Left ventricular (LV) pressure was measured through a cannula inserted via the ventricular apex, right ventricular (RV) pressure by a cannula passed through the free RV wall, and central aortic pressure through a catheter inserted via the femoral artery. All pressures were referred to the middle of the LV cavity and were recorded with the electrocardiogram on a multichannel oscillograph.

Following cross-transfusion with freshly obtained donor blood, recordings were made 30-60 sec after incremental
blood infusions. The relation between left ventricular end-diastolic pressure (LVEDP) and right ventricular end-diastolic pressure (RVEDP) over a range of end-diastolic pressures was obtained, the infusions being continued until the LVEDP was elevated to at least 20 mm Hg.

The heart was then arrested by the intraventricular injection of 25% KCl solution as the aorta was occluded. One curved metal clamp was placed around the atrioventricular groove, care being taken not to compromise the ventricles. Another clamp was placed so as to occlude the aorta and pulmonary artery at the level of the valves. A large-bore cannula was passed into the RV cavity to allow ready control of RV volume, and a wide-bore needle was inserted into the cavity of the LV through its lateral wall. This was attached to a spring-loaded syringe system, whereby 2.0-ml increments of normal saline could be delivered into the ventricle. All of the injectate was recovered after each series of 2.0-ml injections.

In each of eight experiments LV pressure-volume curves were obtained in duplicate with the RV empty; they were then repeated when the RV contained various volumes of fluid. The LV pressure-volume curves were also redetermined intermittently with the RV empty. From these curves a composite curve was constructed for each heart; this curve represented the LV pressure-volume relation appropriate to the balance between left and right ventricular end-diastolic pressures observed previously in the beating heart during blood infusion. In three experiments RV pressure-volume relations were also obtained by serial injections of 2.0 ml into the RV with the LV empty; the curves were then repeated with various volumes of fluid in the LV cavity. The experimental period lasted between 40 and 60 min after arrest of the heart and the diastolic ventricular pressure-volume relations remained stable, without evidence of rigor, throughout each experiment.

**RESULTS**

Figure 1 shows typical ventricular pressure recordings with the introduction of successive 2.0 ml volumes into the left ventricle (LV). The injections were accompanied by stepwise increases in LV pressure. In panel A the right ventricle (RV) was empty, in panel B it contained 40 ml. LV pressure was higher at equivalent LV volumes in panel B, except at LV volumes below 20 ml, and re-
VENTRICULAR PRESSURE-VOLUME RELATIONS

FIG. 2. Right ventricular (RV) pressure-volume relations obtained by injecting 2.0-ml volume increments into the RV, with the left ventricle (LV) empty in A, containing 30 ml in B, and 48 ml in C. The volume contained by the RV is indicated every 10 ml.

plots of the LV pressure-volume relations indicated a difference equivalent to 3.0 ml volume throughout the greater part of the curves. At higher distending pressures (in this experiment at approximately 15 mm Hg), evidence of stress relaxation became evident, a small fall in LV pressure occurring after the pressure step induced by each injection (Fig. 1).

The degree of LV filling also affected RV distensibility. With a volume of 40 ml in the RV and the LV empty in the experiment shown in Fig. 1, the RV intracavitary pressure was 6.3 mm Hg, and with sequential injections of fluid into the LV, the RV pressure increased to 13.5 mm Hg (Fig. 1B). However, the same RV pressure of 13.5 mm Hg that existed with a RV volume of 40 ml in this experiment was associated with a volume of 53.5 ml when the RV pressure-volume curve was subsequently determined with the LV empty (Fig. 2). Typical pressure recordings during injection of 2.0-ml increments of fluid into the RV are shown in Fig. 1, the LV being empty in panel A, containing 30 ml in panel B, and 48 ml in panel C. An LV volume of 30 ml did not appreciably influence the RV pressure-volume relation, but this relation was shifted by 4-6 ml of volume when the LV contained 48 ml.

Figure 2 also illustrates the effect of RV filling on LV distensibility. With the LV volume held at 30 and 48 ml, the LV pressures were 5.0 and 12.8 mm Hg, respectively, with the RV empty. RV volumes below 30 ml did not
The effect of RV filling on the LV pressure-volume relation was also demonstrated in three experiments by rapid decompression of the RV. In the experiment shown in Fig. 4, the LV pressure-volume curve was obtained while the RV contained a constant 50 ml. After 70 ml

<table>
<thead>
<tr>
<th>Dog</th>
<th>LVED, mm Hg</th>
<th>RVED, mm Hg</th>
<th>LV Volume, Corrected, ml</th>
<th>LV Volume Overestimation, RV Empty, ml</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>23 ml</td>
<td>3.6</td>
<td>30.0</td>
<td>4.0</td>
</tr>
<tr>
<td>2</td>
<td>24 kg</td>
<td>3.6</td>
<td>31.0</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>20.5 kg</td>
<td>3.6</td>
<td>35.0</td>
<td>2.0</td>
</tr>
<tr>
<td>4</td>
<td>14.5 kg</td>
<td>3.6</td>
<td>36.0</td>
<td>2.0</td>
</tr>
<tr>
<td>5</td>
<td>13.5 kg</td>
<td>3.6</td>
<td>37.0</td>
<td>3.0</td>
</tr>
<tr>
<td>6</td>
<td>16.0 kg</td>
<td>3.6</td>
<td>39.0</td>
<td>3.0</td>
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<td>7</td>
<td>19.0 kg</td>
<td>3.6</td>
<td>41.0</td>
<td>3.0</td>
</tr>
<tr>
<td>8</td>
<td>18.2 kg</td>
<td>3.6</td>
<td>42.0</td>
<td>3.0</td>
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</table>

LVED = left ventricular end-diastolic pressure; RVED = right ventricular end-diastolic pressure.
had been injected into the LV, 10 ml were rapidly withdrawn from the RV, and the LV pressure fell from 22.6 to 19.0 mm Hg.

The right and left ventricular end-diastolic pressure coexisting over a wide range of cardiac filling in the beating heart and the absolute LV volumes in the arrested heart for all experiments are shown in Table 1; their mean values and standard deviations, expressed per 10 kg of body weight, are presented in Table 2. The corrected LV volumes represent those obtained when the RV was empty minus the volume effect produced by a level of RV filling appropriate to a given LV pressure in the beating heart (composite curve, Fig. 3). The absolute and percentage overestimations of LV volume which result from neglecting the effect of RV filling are also shown in Tables 1 and 2. The mean figures in Table 2 show that the RV filling accompanying a LVEDP of 3 mm Hg had no measurable effect on the LV pressure-volume relation. A slight effect on the relation was evident when the LVEDP was 5 mm Hg, and this effect increased with further ventricular filling to a maximum of 3.9 ± 2.4 (sd) ml, or 7.1 ± 4.7% of left ventricular volume, at an LVEDP of 20 mm Hg. The mean LV pressure-volume relations, uncorrected and corrected for a degree of right ventricular filling appropriate to the relation between RVEDP and LVEDP in the beating heart, are shown in Fig. 5.

**TABLE 2. Effect of right ventricular filling on the left ventricular pressure-volume relation at a physiological balance between right and left ventricular filling: mean values**

<table>
<thead>
<tr>
<th>LVEDP, mm Hg</th>
<th>RVEDP, mm Hg</th>
<th>LV Volume, Corrected, ml/10 kg</th>
<th>LV Volume Overestimation, RV Empty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>ml</td>
</tr>
<tr>
<td>3</td>
<td>1.5±0.6</td>
<td>13.7±3.0</td>
<td>1.8±1.2</td>
</tr>
<tr>
<td>5</td>
<td>2.3±0.8</td>
<td>17.8±3.8</td>
<td>2.5±1.2</td>
</tr>
<tr>
<td>7</td>
<td>3.1±0.9</td>
<td>21.2±5.5</td>
<td>3.9±1.2</td>
</tr>
<tr>
<td>10</td>
<td>4.1±1.0</td>
<td>25.2±5.0</td>
<td>3.6±1.3</td>
</tr>
<tr>
<td>15</td>
<td>5.8±1.0</td>
<td>29.0±5.7</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>7.7±1.4</td>
<td>31.4±6.2</td>
<td></td>
</tr>
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</table>

Values are means ±1 sd. Legends as in Table 1.

At the balance between filling of the right and left ventricles that occurred in the beating heart, the capability of right ventricular filling to decrease left ventricular distensibility was not discernible at an LVEDP of 3 mm Hg, but an effect became apparent at an LVEDP of 5 mm Hg, and increased to 7.1 ± 4.71% or left ventricular volume at a LVEDP of 20 mm Hg. This means that at LVEDP of 20 mm Hg, the volume contained by the left ventricle was 7.1% larger when the right ventricle was empty than when the right ventricle was filled to the pressure observed to accompany an LVEDP of 20 mm Hg in the beating heart. The particular balance of right and left ventricular filling pressures observed herein approximates that usually found in the open-chested animal, when the pericardium is open (2, 19). Obviously, however, this balance must depend on the loading conditions and the inotropic state of each ventricle, as well as on the state of the pericardium (2, 3). Simultaneous equivolume filling of the right and left ventricles from initial volumes of zero was also examined (Fig. 6), but this method of filling the ventricles appears relevant to the contracting heart only if it is assumed that the right and left ventricular ejected fractions are equal.

**DISCUSSION**

The present study has examined quantitatively the effect of filling either the left or right ventricle on the distensibility of the opposite ventricle, with particular reference to the balance between the filling of these chambers which occurs in the intact circulation. The magnitude of this influence on the ventricular pressure-volume relation varies directly with the degree of filling of the other ventricle, and whereas it is minimal at the usual physiological levels of ventricular filling, it becomes significant at abnormally elevated end-diastolic volumes.
The observed displacement of the ventricular pressure-volume relations may be attributed to the presence of a common interventricular septum and to the interdigitation of muscle fiber bundles between the ventricles (12, 16, 20, 22). The effect is a direct mechanical one, resulting from this close anatomical relation of the two ventricles, and should be operative in the intact mammalian heart under all circumstances. Hence, another mechanical factor must be added to those already known to influence the relation between ventricular diastolic pressure and volume, such as incomplete ventricular relaxation (6, 17), variable perfusion of the coronary circulation (7), and myocardial edema (7). In addition, cardiac muscle in vitro (5, 15, 23, 26) and in the intact ventricle (1, 10, 11, 13, 23, 25) shows not only elasticity but also viscous characteristics, including hysteresis and stress relaxation; the latter effect was evident at high ventricular filling pressures in the present study (Fig. 1). The direct mechanical effects of ventricular distension on the pressure-volume relation of the opposite ventricle, demonstrated in the present study, have been less well appreciated. It may be presumed that changes in sarcomere length parallel changes in ventricular volume rather than in ventricular diastolic pressure, when volume and pressure change independently. Hence, when the pressure-volume relation is influenced by filling of the opposite chamber, ventricular diastolic pressure is not a good index of sarcomere length, which is the specific length determinant of cardiac muscle function (24). The importance of the mechanical interplay between the two ventricles, and the interpretive difficulty imposed, is well illustrated by a recent study in which right ventricular distension was shown to depress the left ventricular function curve, i.e., the relation between left ventricular stroke work and LVEDP (18). This effect may not have been the result of depression of left ventricular contractility per se, but rather due at least in part to a dissociation of left ventricular diastolic pressure and volume induced by the right ventricular distension. This, then, is an effect that must be considered whenever the function of either ventricle is examined over a range of filling pressures in the intact heart.

Correlation of the filling pressure of a ventricle with its pressure-volume relation to obtain an estimate of ventricular volume was suggested as early as 1895 by Frank (9), in commenting on the pressure-volume relations obtained by Dreser (8). The principle has been used recently in this laboratory to estimate the volume of the contracting left ventricle during bypass of the right heart (21), a preparation in which right ventricular filling therefore was not a variable. The effect of right ventricular filling would require consideration, however, if the passive pressure-volume relation were used to estimate left ventricular volume in the intact animal. The present studies indicate that in the normal heart under circumstances conditions the effect is reproducible and quantitatively similar from one animal to another.

The interrelations between right and left ventricular filling and distensibility could be particularly important in the presence of selective distension or failure of either ventricle in disease states. In 1910 Bernheim postulated that left ventricular hypertrophy or dilatation of various etiologies could compress the right ventricle, thereby limiting right ventricular performance and producing systemic venous congestion and congestive cardiac failure (4). This investigator did not consider the right ventricular cavity in his patients to be dilated but, rather, to be compressed by the left ventricle. Although this specific syndrome does not appear to be common, Bernheim's suggestion that the filling of one ventricle affects the other appears to warrant more attention than it has received. The present results indicate the extent to which acute ventricular distension may influence the pressure-volume relation of the opposite ventricle; thus, a degree of ventricular filling associated with a normal end-diastolic pressure when the other ventricle is of relatively normal size may be associated with a grossly abnormal end-diastolic pressure when the opposite ventricle is distended. This mechanism may contribute substantially to the frequent appearance of systemic venous congestion and congestive heart failure shortly after the onset of left ventricular failure, as in acute myocardial infarction. In this situation, the right ventricle may be able to work against a somewhat increased pulmonary arterial pressure from an initially normal filling pressure, but when the effect of acute left ventricular distension is superimposed, the right ventricular volume and sarcomere length necessary to maintain this level of right ventricular function may be associated with an ab-
normally elevated right ventricular diastolic pressure; systemic venous congestion then ensues. Similarly, left ventricular filling pressure could be elevated by acute distension of the right ventricle, as in acute pulmonary embolism. Although there must be reservation in extrapolating the results of the present acute experiments to disease states, the anatomy of the human ventricle is similar to that of the dog (16, 20) and the principles described in the present experiments may well influence the hemodynamic conditions in acute and chronic congestive cardiac failure in man.

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REFERENCES