Ventricular Volume of Nonbeating Excised Dog Hearts in the State of Elastic Equilibrium

By G. A. Brecher, M.D., Ph.D., H. Kolder, M.D., and A. D. Horres, Ph.D.

ABSTRACT

The volume in the left ventricle and that in the right ventricle were measured statically starting from zero transmural pressure, when the ventricle is in the state of elastic equilibrium, to a negative transmural pressure of 30 mm Hg. Freshly excised dog hearts were submerged in Ringer's solution at 10°C to establish zero transmural pressure, to offset the contribution of the weight of the ventricular walls on the shape of the ventricle, and to retard the onset of postmortem changes. The volume was approximated by an equation which included a power function of the body weight and another of the ventricular weight. For male dogs, the left ventricle when in the state of elastic equilibrium contained a mean volume of 14.5 ml for a body weight of 10 kg and a ventricular weight of 58 g; the corresponding figure for the right ventricle was 12.2 ml. In a quiescent heart below a certain ventricular volume, potential energy will be stored in structural elements of the ventricle wall that will facilitate the filling of the ventricle.

ADDITIONAL KEY WORDS

vis a fronte nonbeating heart elastic recoil ventricular filling

The state of elastic equilibrium of a cardiac ventricle is defined as the condition in which its transmural pressure is zero and no stress is applied on its structural elements. This condition can be approached by submerging a freshly excised, nonbeating ventricle in Ringer's solution before onset of rigor mortis. Brecher and Kissen (1) established S-shaped pressure-volume curves of canine left and right ventricles, extending the usual measurements into the domain of ventricular volumes less than those contained in the state of elastic equilibrium. Rushmer et al. (2) referred to anatomical evidence that contraction, resulting in a volume which is less than the ventricular volume in the state of elastic equilibrium, could store potential energy in the strained elastic elements. Diastolic recoil would then tend to produce a negative transmural pressure of the ventricle, increase the atrioventricular pressure difference, and facilitate the filling of the ventricle through a "vis a fronte," i.e. suction. A graphic representation of the concept was previously published by Kolder et al. (3). The purpose of the present study is to measure under controlled conditions the left and right ventricular volume in the state of elastic equilibrium and to relate the measured volumes to body weight, weight of both ventricles, and sex. This statistical information will be of value in assessing the ventricular volume at which elastic forces in the ventricular wall start contributing to diastolic filling.

Method

The technique used for the present experiments is similar to that previously described (3). Dogs were anesthetized with pentobarbital (30 mg/kg body weight, iv) and rapidly exsanguinated. The chest was opened and the heart removed.
without the pericardium. The aorta was ligated for studies on the left ventricle and the pulmonary artery was ligated for studies on the right ventricle. A Tygon cannula was secured in the atrioventricular orifice by means of a ligature around the atrioventricular groove, avoiding any deformation of the ventricles. The heart was transferred to a constant temperature bath containing Ringer's solution at 10°C ± 0.25. From previous experiments (3, 4) it is known that no important changes occur in the pressure-volume curve of excised canine ventricles for at least 3 hours at 10°C. The ventricular cannula was connected to a graduated burette, and the fluid levels of bath and burette equalized to establish zero transmural pressure across the ventricular wall. Lowering of the burette decreased the ventricular pressure and permitted measurement of both pressure difference and volume displacement. The determinations were made at a negative transmural pressure of 30 mm Hg. This limit was selected since earlier experiments (1, 3) indicated that volume changes are negligible with further pressure reduction. Volume measurements were restricted to the range of negative transmural pressures. At least four series of pressure-volume measurements were made on each ventricle. The hearts of 28 male mongrel dogs and of 19 female mongrel dogs of various ages were used for the study. The body weight ranged from 5.3 kg to 26 kg. Measurements were available from 58 additional dogs for inclusion into the analysis of the relationship between body weight and ventricular weight. Pressure measurements were made to the nearest millimeter of water, and volume measurements to 0.2 milliliter. The body weight balance had units of 250 g and the ventricular weight balance had units of 1 g. Ventricles were separated from the remaining part of the heart by transection through the atrioventricular groove. The ventricular weights were corrected for the estimated increase in weight with time of submersion because of fluid uptake from Ringer's solution (3). The raw data were transformed into logarithms. The following empirical equation in exponential form:

\[ VVL = 0.75 (BW)^{0.546} (VW)^{0.418}, \]  

where \( VVL \) = left ventricular volume in milliliters, \( BW \) = body weight in kilograms, and \( VW \) = weight of both ventricles in grams.

The following mathematical model was used to be fitted to data from measurements of the ventricular volume in the state of elastic equilibrium and for the computer analysis of the relationship between body weight and ventricular weight:

\[ \log_e (y) = \beta_0 + \beta_1 \log_e (BW) + \beta_2 \log_e (VW), \]  

where \( y \) = ventricular volume in milliliters and \( \beta_0, \beta_1, \beta_2 \) = coefficients. The equation used for computation (1a) and statistical information are listed in the Appendix; the statistical information pertains to the parameter estimates in that form of the equation.

The model accounts for 99.8% of the observed variance. The \( t \)-tests indicate that body weight and ventricular weight enter the regression analysis as significant variables, while the contribution of the coefficient \( \beta_0 \) to the VVL has a \( P < 0.05 \). The sum of the squared errors (SSE) and the percent of variation explained by the model (\( R^2 \)) decrease and increase respectively by adding the coefficient \( \beta_0 \), i.e. the predictive value of the equation is improved by inclusion of \( \beta_0 \). Body weight is the first variable to enter this stepwise regression analysis, and is, therefore, the most important variable determining the left ventricular volume.

The volume contained in the canine right ventricle in the state of elastic equilibrium can be approximated by the following empirical equation:

\[ VVR = 0.28 (BW)^{-0.082} (VW)^{1.332}, \]  

where \( VVR \) = right ventricular volume in milliliters, and the other symbols are identical with those used for equation 1. (Also see Appendix for equation 3a.)

The model accounts for 99.6% of the observed variance. The \( t \)-tests indicate that the
ventricular weight enters the regression analysis as a significant variable, while the contribution of the body weight and of the coefficient $\beta_0$ to the VVR has a $P < 0.05$. The sum of the squared errors (SSE) and the percent of variation explained by the model ($R^2$) decrease and increase respectively by adding the body weight and the coefficient $\beta_0$. Ventricular weight is the first variable to enter this stepwise regression analysis, and is, therefore, the most important variable determining the right ventricular volume.

The $F$-tests for sex differences in the predicted volume of left and right ventricles is not significant at the level $P = 0.05$, but, as shown below, the relation of ventricular weight to body weight is dependent on sex.

Two additional equations were computed to facilitate the use of equations 1 and 3 when no information is available on the ventricular weight.

$$V_{WM} = 5.37 (BWM)^{1.085}$$

$$V_{WF} = 8.56 (BWF)^{0.811}$$

where $V_{WM}$ = weight in grams of both ventricles of male dogs, $V_{WF}$ = weight in grams of both ventricles of female dogs, $BWM = $ body weight in kilograms of male dogs, and $BWF = $ body weight in kilograms of female dogs.

The mathematical model (equation 6) was:

$$\log_e z = \beta_0 M + \beta_0 F + \beta_M \log_e (BW) + \beta_F \log_e (BW),$$

where $z = VW =$ weight of both ventricles in grams, $M = 1$, $F = 0$, for male dogs; and $F = 1$, $M = 0$, for female dogs.

The equations used for computation (equations 4a and 5a) and statistical information are listed in the Appendix; the statistical information pertains to the parameter estimates in that form of the equations.

The heart weight = 1.34 the weight of both ventricles in this series of observations. The $F$-test for sex differences in the predicted weight of both ventricles is significant at the level $P < 0.005$.

Discussion

The reported experiments furnish information about the ventricular volume in the state of elastic equilibrium, in a static condition, in the absence of stretching or deforming forces; and the dependence of this ventricular volume on body weight and ventricular weight. It can be predicted that in a male dog that weighs 10 kg both ventricles will weigh 58 g (50 to 67; ±1 se), the left ventricular volume will be 14.5 ml (12.8 to 16.4; ±1 se), and the right ventricular volume will be 12.2 ml (10.2 to 14.7; ±1 se).

Results of recent measurements of the left and right ventricular end-systolic volume obtained with two techniques are listed in Table 1 (5-15). They can be compared with results from experiments with mechanical emptying of the ventricles and establishment of the ventricular volume in the state of elastic equilibrium (Table 2 (14, 16)). Results presented by Kolder and associates (3) indicate that the variation with temperature of the ventricular volume of the quiescent heart in the state of elastic equilibrium is within the measurement error of the technique used.

The indicator-dilution techniques yield larger estimates of end-systolic volumes; this suggests that the end-systolic volume exceeds the volume in the elastic equilibrium, and, therefore, elastic forces would not contribute to diastolic filling. Indicator-dilution techniques are often used in closed chest preparations where the negative transthoracic pressure contributes to the negative transmural ventricular pressure. As seen in Figure 2 of reference 3, an increase of the negative transthoracic pressure by 5 mm Hg would increase the fluid volume of the left ventricle by approximately 14 ml/10 kg body weight beyond that contained in its state of elastic equilibrium. If such increased negative transthoracic pressure would persist continuously, a larger ventricular volume would result than the one reported in the present study for the state of elastic equilibrium. Under this assumption the resulting ventricular volume,
**TABLE 1**

*End-Systolic Ventricular Volume Determined with Two Methods*

<table>
<thead>
<tr>
<th>Method</th>
<th>End-systolic volume of left ventricles (ml/10 kg body weight)</th>
<th>End-systolic volume of right ventricles (ml/10 kg body weight)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indicator</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dilution</td>
<td>13.2</td>
<td>13.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13.8</td>
<td>15.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>19.5</td>
<td>14.9</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>19.9</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>22.6</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>24.4</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>X-ray</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cardiography</td>
<td>4.2</td>
<td>6.9</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>6.9</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12.0</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13.4</td>
<td>17.5</td>
<td>13</td>
</tr>
</tbody>
</table>

The values have been extracted and averaged from published data and are linearly normalized to 10 kg of body weight.

**TABLE 2**

*Ventricular Volume in State of Elastic Equilibrium*

<table>
<thead>
<tr>
<th>Method</th>
<th>Left ventricular volume (ml/10 kg body weight*)</th>
<th>Right ventricular volume (ml/10 kg body weight*)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>4.9</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>emptying</td>
<td>6.2</td>
<td>3.1</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>9.5</td>
<td>1.0</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>14.5</td>
<td>1.2</td>
<td>Present study</td>
</tr>
</tbody>
</table>

The values have been extracted and averaged from published data and are linearly normalized to 10 kg of body weight.

*Measured at zero transmural pressure.

determined by the elastic force and the negative transmural pressure, would exceed the end-systolic volume, as found by dilution techniques.

Determinations of the end-systolic volume by X-ray cardiography of beating hearts indicate that end-systolic volumes are less than the ventricular volumes found in the elastic equilibrium state of quiescent hearts. The level of anesthesia, the heart rate, the degree of sympathetic innervation and the dynamic component of elastic recoil may all modify the measurements of beating hearts. For the present experiments only that force is evaluated which determines the ventricular volume when the main functional activity of the heart muscle (rhythmic contraction) and the effect of factors controlling it, ceased. Previous measurements of the ventricular volume of quiescent hearts in the state of elastic equilibrium by mechanical emptying established volumes which are considerably smaller than the volumes measured in the present experiments. Incomplete emptying or incomplete relaxation might cause this difference. Insufficient information about the actual conditions during previous experiments does not permit ruling out that incomplete emptying occurred during earlier experiments. Incomplete relaxation, on the other hand, would indicate that other forces, e.g., tonic contraction, were still active during these measurements, tending to reduce the ventricular volume. The results from present experiments would then establish an upper limit to which the elastic force of structural elements would
move the ventricular wall if not opposed by other forces.

Any change in body weight affects the left ventricular volume to a greater extent than the right ventricular volume. Stated differently: the volume contained in the right ventricle in the state of elastic equilibrium is more closely related to the ventricular weight than to the body weight. The following hypothesis is suggested to explain the dependence of the volume in the left ventricle in the state of elastic equilibrium on body weight and the dependence of the volume in the right ventricle on ventricular weight. The size of the animal, measured as body weight, or other factors strongly related to the body weight, requires a certain left ventricular stroke volume. This finally determines the size of the left ventricle in its state of elastic equilibrium. The dependence of the volume in the right ventricle on ventricular weight, on the other hand, may be interpreted as passively following the size of the left ventricle, and it may be the consequence of the fact that when body weight increases there is a proportionately smaller increase of resistance in the pulmonary circulation than in the systemic circulation.

**Appendix**

Equation 1a was used for the computer analysis of the left ventricular volume:

$$\log_e (VVL) = -0.2823 + 0.5465 \log_e (BW) + 0.4175 \log_e (VW),$$

with $$SE(y_i - \hat{y}_i) = 0.1244; \ SE\beta_0 = 0.3529; \ t = 1.59; \ SE\beta_1 = 0.4789; \ t = 1.43; \ SE\beta_2 = 0.4613; \ t = 2.89; \ R^2 = 0.9990; \ N = 19.$$ 

Equation 3a was used for the computer analysis of the right ventricular volume:

$$\log_e (VVR) = -1.3632 - 0.6824 \log_e (BW) + 1.3318 \log_e (VW),$$

with $$SE(y_i - \hat{y}_i) = 0.1832; \ SE\beta_0 = 0.8592; \ t = 1.59; \ SE\beta_1 = 0.4789; \ t = 1.43; \ SE\beta_2 = 0.4613; \ t = 2.89; \ R^2 = 0.9990; \ N = 19.$$ 

Equation 4a and 5a were derived from the computer analysis of the relationship between body weight, ventricular weight and sex, according to equation 6.

$$\log_e (VWM) = 1.6814 + 1.0351 \log_e (BWM),$$

with $$SE(y_i - \hat{y}_i) = 0.1440; \ SE\beta_0 = 0.1344; \ t = 12.5; \ SE\beta_F = 0.1757; \ t = 12.2; \ SE\beta_M = 0.0532; \ t = 19.4; \ SE\beta_L = 0.0753; \ t = 10.8; \ R^2 = 0.9989; \ NM = 59; \ NF = 46.$$ 

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**References**


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