Left Heart Volume Estimation in Infancy and Childhood

Reevaluation of Methodology and Normal Values

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SUMMARY

Left ventricular (LV) volume determinations by the area-length method were reevaluated in postmortem studies of left ventricles ranging from 0.5 to 90 cm³ absolute volume. The regression equation relating known and calculated volumes for calculated volumes <15 cm³ (V' = 0.733V) was found to be significantly different from that for calculated volumes >15 cm³ (V' = 0.974V - 3.1). From these equations, normal values for cineangiographic LV end-diastolic volume (LVEDV), LV ejection fraction (LVEF), LV systolic output (LVSO), LV mass (LVM), and left atrial maximal volume (LAMax) were derived from 56 children (19 < 2 years) with normal left ventricles who underwent cardiac catheterization. Values for LVEDV/BSA were significantly less for infants (< 2 years) than for older children (42 ± 10 versus 73 ± 11 cm³/m², P < 0.001). Values for LAMax/BSA were also less for infants than for older children (26 ± 5 versus 38 ± 8 cm³/m², P < 0.001), and LVEF was significantly increased for infants (0.68 ± 0.05 versus 0.63 ± 0.05, P < 0.01). The values for LVM/BSA (88 ± 12 g/m²) and LVSO/BSA (4.42 ± 0.95 liters/min/m²) were not significantly different for infants and older children. Multiple regression equations were derived for the prediction of normal volume and mass variables from a patient's height, weight, and age. The predicted values can be obtained from nomograms, and estimations of normalcy can be made by comparisons of observed and predicted values with the 95% limits as defined.

Additional Indexing Words:
Left ventricular volume
Left atrial volume
Ejection fraction
Normal standards in infancy
Left ventricular mass

Previous work in our laboratory has indicated that children less than 2 years of age with normal left hearts have a smaller normalized left ventricular end-diastolic volume (LVEDV) and a higher ejection fraction than normal older children. Additional determinations of left ventricular volumes in infants less than 3 months of age, however, have indicated probable underestimation of small volumes for this age group with the previously reported regression equation used to correct calculated biplane cineangiographic volumes. Because the regression equation is an integral part of ventricular volume determinations, the reliability of this equation is an important determinant of the accuracy of the method. The equation currently used (V' = 0.930V - 2.0 cm³, where V = calculated volume and V' = corrected volume) will yield a negative value for the corrected volume.
volume when the calculated volume is less than 2.1 cm$^3$. Since in a number of newborn infants calculated end-systolic volumes were found to be less than 2.1 cm$^3$, it became apparent that a reevaluation of the regression equation relating calculated and known volumes was needed for the accurate use of this method in small hearts of neonates and young infants.

An additional problem in defining normal standards for infants and children is the difficulty in normalizing data for patients of different age and size. The possible errors inherent with the use of estimated body surface area for this purpose have been discussed, and the use of multiple regression techniques has been suggested as an alternate method for defining normal standards.$^{2,3}$

The purpose of this investigation, therefore, was first to evaluate the accuracy of left ventricular volume estimation in small hearts using in vitro techniques, and then to reassess previously derived standards of normalcy for both left ventricular and left atrial volume variables in the infant age group using a larger sample of patients and employing multiple regression techniques.

**Methods**

The methods and results of the in vitro study on postmortem left ventricles will be presented first. Based on these results, the patient data will then be presented and discussed.

**Postmortem Volume Calculations**

Postmortem studies were performed on left ventricles from 62 dogs and 10 patients without

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**Figure 1**

Vinyl rubber casts of left ventricles. A–D = human casts; E–H = dog casts. Measured volumes: (A) 1.2 cm$^3$; (B) 10 cm$^3$; (C) 27 cm$^3$; (D) 21 cm$^3$; (E) 12 cm$^3$; (F) 1.8 cm$^3$; (G) 16 cm$^3$; and (H) 14 cm$^3$.
LEFT HEART VOLUME ESTIMATION

anatomical evidence of heart disease. Data obtained were of two types: ventricles injected with known amounts of barium sulfate as previously described\(^1\) and left ventricular casts made with liquid room temperature vulcanizing silicone rubber (General Electric RTV No. 11).\(^4\)

There were only minor differences in gross morphology of dog and human specimens (fig. 1).

Biplane cinecardiograms were taken of the casts and injected specimens in the estimated anteroposterior and lateral projections which the ventricle would have occupied in vivo. A calibrated grid was filmed for each study at the position the heart or heart cast occupied and was used to correct for image magnification.\(^3\)

Ventricular volume was calculated by the area-length method\(^5\) where

\[
V = \frac{0.847 \times \text{Aap} \times \text{A lat}}{\text{Shortest LL (AP or lat)}}
\]

Aap is the area corrected for magnifications of the ventricular image in the anteroposterior view; A lat is the corrected area in the lateral view; and LL is the corrected longest measure length. The measured or corrected volume, \(V'\), was known in the injected hearts since carefully calibrated injections of barium sulfate were used. The measured or corrected volume of the casts was obtained by water displacement or by weight in grams divided by the specific gravity of the vulcanized silicone rubber determined in our laboratory (1.235 g/cm\(^3\)). This latter method of determining cast volume was necessary in small casts because of the inaccuracies of determining water displacement at very low values.

**Results of Calculations**

Initial statistical analysis revealed no significant differences in the regression equations relating calculated and measured volumes for barium injected ventricles versus silicone casts (\(P > 0.5\)) or for dog ventricles versus human specimens (\(P > 0.4\)). Therefore, all data were analyzed together. There was a linear relationship between calculated volume (\(V\)) and measured volume (fig. 2). In plotting the data, there appeared to be a different slope to the relationship of calculated and measured volume for small and large volumes. Therefore, the data were divided

![Figure 2](http://circ.ahajournals.org/)

*Figure 2*

Measured volume as a function of calculated volume of postmortem left ventricles of both dogs and humans. There are significantly different regression equations for calculated volumes <15 cm\(^3\) and volumes >15 cm\(^3\).
into subgroups according to the calculated volume, separate regression equations were derived for each subgroup, and the separate equations were compared statistically as to whether or not they were significantly different from one another. Subgroups were derived as follows: calculated volume <10 cm$^3$ and >10 cm$^3$, <11 cm$^3$ and >11 cm$^3$, etc., up to calculated volume <20 cm$^3$ and >20 cm$^3$. Regression equations were significantly different ($P < 0.01$) for the smaller and the larger volume subgroups of each pair thus derived. The optimal separation of large and small volume subgroups in terms of the smallest residual error of volume estimation when comparing one equation with another occurred with the grouping calculated volume <15 cm$^3$ and >15 cm$^3$ ($P < 0.001$). The average residual error in volume estimation for calculated volumes <15 cm$^3$ was only 0.51 cm$^3$ or 12.7% of measured volume with the use of the separate regression equations. The average residual error in volume estimation for calculated volumes >15 cm$^3$ was 2.4 cm$^3$ or 9.3%.

Because of the observed increase in accuracy of volume estimations for small volumes (calculated volumes <15 cm$^3$), it was decided to use the two separate equations as derived for correction of all calculated volumes in patients. For calculated volumes <15 cm$^3$: $V = 0.733 (V)$, where $V$ is the corrected volume and $V$ is the calculated volume. The y intercept (+0.03 cm$^3$) was not significantly different from zero and, therefore, was eliminated. For calculated volumes >15 cm$^3$: $V = 0.974 (V) - 3.1 cm^3$.

Because of this change in methodology, normal values previously derived for left ventricular end-diastolic volumes, ejection fraction, output, and wall mass were reevaluated. In addition, because of the increase in the number of small patients’ data available, left atrial volume also was reevaluated.

**Patient Group**

Fifty-six patients ranging in age from 1 day to 16 years with normal left hearts were included in this analysis (table 1). Twenty-six of these patients have been included in a previous investigation. The following diagnostic categories were included in the normal group: vascular ring (eight), pulmonary sequestration or other pulmonary anomaly (seven), mild pulmonary stenosis with right ventricular pressure <60 mm Hg (13), atrial septal defect with left-to-right shunt <35% of pulmonary flow (seven), and patients with

### Table 1

**Vital Statistics, Hemodynamics, and Normalized Left Heart Volume Data**

<table>
<thead>
<tr>
<th></th>
<th>Patients &lt; 2 yr (n = 19)</th>
<th>Patients &gt; 2 yr (n = 37)</th>
<th>P</th>
<th>All patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>0.59 ± 0.55</td>
<td>7.16 ± 3.21</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Heart rate (beat/min)</td>
<td>142 ± 14</td>
<td>99 ± 15</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>RVP (mm Hg)</td>
<td>36 ± 12/6 ± 3</td>
<td>35 ± 11/7 ± 4</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>LVP (mm Hg)</td>
<td>96 ± 13/12 ± 5</td>
<td>99 ± 11/11 ± 4</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>AP (mm Hg)</td>
<td>93 ± 16/57 ± 12</td>
<td>100 ± 10/63 ± 9</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>Hgb (g/100 ml)</td>
<td>11.9 ± 2.6</td>
<td>12.1 ± 2.8</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>LVEDV/BSA (cm$^3$/m$^2$)</td>
<td>42 ± 10</td>
<td>73 ± 11</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>LVEDV/weight (cm$^3$/kg)</td>
<td>2.24 ± 0.45</td>
<td>2.84 ± 0.43</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>LVEDV/height (cm$^3$/cm)</td>
<td>0.23 ± 0.08</td>
<td>0.54 ± 0.12</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>LVEF</td>
<td>0.68 ± 0.05</td>
<td>0.63 ± 0.05</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>LVSO (liter/min/m$^2$)</td>
<td>4.21 ± 0.95</td>
<td>4.53 ± 0.94</td>
<td>ns</td>
<td>4.42 ± 0.95</td>
</tr>
<tr>
<td>(liter/min/kg)</td>
<td>0.22 ± 0.04</td>
<td>0.18 ± 0.04</td>
<td>&lt;0.01</td>
<td></td>
</tr>
<tr>
<td>(liter/min/cm)</td>
<td>0.02 ± 0.007</td>
<td>0.03 ± 0.007</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>LVMass (g/m$^2$)</td>
<td>96 ± 11 (n = 11)</td>
<td>86 ± 11 (n = 34)</td>
<td>ns</td>
<td>88 ± 12</td>
</tr>
<tr>
<td>(g/kg)</td>
<td>4.84 ± 0.75</td>
<td>3.32 ± 0.50</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>(g/cm)</td>
<td>0.49 ± 0.06</td>
<td>0.63 ± 0.13</td>
<td>&lt;0.01</td>
<td></td>
</tr>
<tr>
<td>LAMax (cm$^3$/m$^2$)</td>
<td>26 ± 5 (n = 16)</td>
<td>35 ± 8 (n = 25)</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>(cm$^3$/kg)</td>
<td>1.44 ± 0.30</td>
<td>1.48 ± 0.32</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>(cm$^3$/cm)</td>
<td>0.14 ± 0.05</td>
<td>0.27 ± 0.07</td>
<td>&lt;0.001</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: RVP = right ventricular pressure; LVP = left ventricular pressure; AP = aortic pressure; Hgb = hemoglobin; LVEDV = left ventricular end-diastolic volume; LVEF = left ventricular ejection fraction; LVSO = left ventricular systolic output; LVM = left ventricular muscle mass; LAMax = left atrial maximal volume; ns = not significant ($P > 0.05$).

*Mean ± sd.
heart murmurs and abnormal electrocardiograms but without atrioventricular conduction disturbances, whose catheterization data revealed no hemodynamic cardiovascular abnormalities (21). Nineteen patients were less than 2 years of age (range, 1 day–20 months) and comprise group I. Group II included 37 patients who were 2 years of age or older (range, 2–16 years).

**Data Acquisition**

All data were derived from diagnostic cardiac catheterizations. Six patients were studied with only local anesthesia; 13 patients were studied with meperidine (1 mg/kg) and/or promethazine (<1 mg/kg) premedication given at least 1 hr before the procedure; and 37 patients were studied with light nitrous oxide and/or halothane (<0.5%) general anesthesia.

Left heart volume data were obtained from the first biplane cineangiocardiograph (anteroposterior and lateral, 60 frames/sec) of the study filmed at least 60 min after the beginning of the procedure. Volumes were derived in the absence of ectopic beats from the levogram phase of pulmonary artery (PA) cines using 1–1.25 ml/kg Hypaque-M (sodium and meglumine diatrizoates). Right and left heart pressures were recorded just prior to the PA cine, using NIH catheters (no. 5, 6, or 7) or a catheter tip transducer.* Zero pressure was referenced to the midchest. The electrocardiogram, cine exposure, and left ventricular pressure when feasible, were recorded during the cine. The details of this system have been described previously.1

After each study, a metal grid with 625 squares (1 cm × 1 cm) was filmed at the midchest position in each projection and used to correct for X-ray magnification.

**Volume Calculations**

Left ventricular end-diastolic volume (LVEDV), left ventricular end-systolic volume (LVESV), and left atrial maximal volume (LAMax) were calculated for two or more consecutive beats using the area-length method,5 and average values were obtained by a modification of the method of Rackley et al.6 in which the lateral wall thickness was measured on the anteroposterior film at a position directly perpendicular to the midpoint of the longest measured length. Left ventricular volumes were corrected by the regression equations given corrected by a previously derived equation.1

**Statistical Methods and Normalization of Data**

All volume and mass variables were divided by height, weight, and body surface area (BSA) in order to normalize data for patients of different sizes. These new volume and mass values for groups I and II were compared by Student's t-test. In addition, both linear and quadratic single and multiple regression analyses8 were applied to the volume and mass data with height, weight, BSA, age, and heart rate as independent variables, as a separate means of assessing alterations in normal values with age and size.

An initial analysis was performed to test whether there was an effect of general anesthesia on the variables studied. There were no significant differences (P > 0.1) in any of the normalized volume variables (Vol/BSA) or in ejection fraction obtained with or without general anesthesia for either of the age groups studied, and, therefore, all data were analyzed together.

**Results**

Left ventricular end-diastolic volume (LVEDV) was linearly related to BSA, as shown in figure 3. Deviation from the regression line in absolute terms increases with increasing size, but the percent deviation does not change.

**Figure 3**

Left ventricular end-diastolic volume as a function of body surface area. The regression equation ±10 and 20% of predicted values is shown.

*Circulation, Volume XLIII, June 1971

*SF1, Statham Products, Inc.

†Nomograms for the rapid derivation of predicted normal values using the derived regression equations are available and will be supplied on request to the authors.
Table 2
Regression Equation for Prediction of Normal Volume Variables

<table>
<thead>
<tr>
<th>Volume Variable</th>
<th>Equation</th>
<th>( r^2 )</th>
<th>SEE</th>
<th>( P )</th>
<th>95% limits*</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVEDV (cm³)</td>
<td>( \text{LVEDV (cm}^3\text{)} = 2.67(\text{wt}) - 0.43(\text{ht}) + 9.40(\text{age}) + 19.3 )</td>
<td>0.893</td>
<td>2.7</td>
<td>&lt;0.001</td>
<td>74–128% of normal</td>
</tr>
<tr>
<td>(2 yr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LVEDV (cm³)</td>
<td>( \text{LVEDV (cm}^3\text{)} = 1.38(\text{wt}) + 0.73(\text{ht}) - 1.94(\text{age}) - 42.3 )</td>
<td>0.874</td>
<td>9.9</td>
<td>&lt;0.001</td>
<td>74–128% of normal</td>
</tr>
<tr>
<td>(2 yr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LVSO (liters/min)</td>
<td>( \text{LVSO} = 0.21(\text{wt}) - 0.002(\text{wt})^2 + 0.003(\text{ht}) - 0.08 ) (all patients)</td>
<td>0.835</td>
<td>0.690</td>
<td>&lt;0.001</td>
<td>62–138% of normal</td>
</tr>
<tr>
<td>LVM (g)</td>
<td>( \text{LVM} = 2.11(\text{wt}) + 0.16(\text{ht}) + 7.0 ) (all patients)</td>
<td>0.927</td>
<td>8.8</td>
<td>&lt;0.001</td>
<td>76–124% of normal</td>
</tr>
<tr>
<td>LAMax (cm³)</td>
<td>( \text{LAMax (cm}^3\text{)} = 1.23(\text{wt}) - 0.07(\text{ht}) + 2.22(\text{age}) + 4.1 ) (2 yr)</td>
<td>0.841</td>
<td>1.8</td>
<td>&lt;0.001</td>
<td>68–132% of normal</td>
</tr>
<tr>
<td>LAMax (cm³)</td>
<td>( \text{LAMax (cm}^3\text{)} = 0.60(\text{wt}) + 0.49(\text{ht}) - 0.71(\text{age}) - 34.8 ) (2 yr)</td>
<td>0.664</td>
<td>7.8</td>
<td>&lt;0.001</td>
<td>63–137% of normal</td>
</tr>
</tbody>
</table>

Abbreviations: LVEDV = left ventricular end-diastolic volume; LVSO = LV systolic output; LVM = LV wall mass; LAMax = left atrial maximal volume; SEE = standard error of estimate; wt = body weight in kg; ht = body height in cm; age = age in years.

*95% limits are for observed volume variable/predicted volume variable × 100.

Normalized LVEDV was significantly less in terms of cm³/BSA, cm³/weight, and cm³/height for infants less than 2 years than for children older than 2 years (Table 1). The average LVEDV/BSA for infants under 2 years was 42 ± 10 cm³/m², and for children over 2 years it was 73 ± 11 cm³/m² (\( P < 0.001 \)).

Because of the difficulty in precise estimations of body surface area, LVEDV was related directly to height, weight, age, and heart rate by multiple regression analysis. This analysis revealed that height, weight, and age were significantly related to LVEDV, but that the further addition of heart rate did not improve this relationship. Although separate equations for the infant and older child age groups were not significantly different in terms of regression coefficients or intercept, the residual difference between observed and predicted LVEDV was reduced considerably (\( P < 0.001 \)) when separate equations were used (Table 2). From these data, 90% of all normal patients’ LVEDVs would be expected to fall between 78 and 123% (\( \bar{x} \pm 1.65 \text{ sd} \)) of predicted values, and 95% between 74 and 128% of predicted values (\( \bar{x} \pm 2 \text{ sd} \)) (Table 2).

Left ventricular ejection fraction (LVEF) decreased linearly with increasing age (\( r = 0.523 \), \( P < 0.001 \)), height (\( r = 0.513 \), \( P < 0.001 \)), BSA (\( r = 0.512 \), \( P < 0.001 \)) (Fig. 4), weight (\( r = 0.494 \), \( P < 0.001 \)), and heart rate (\( r = 0.474 \), \( P < 0.001 \)). The ejection fraction averaged 0.68 ± 0.05 in infants < 2 years and 0.63 ± 0.05 in older children (\( P < 0.001 \)).

Left ventricular systolic output (LVSO) was linearly related to BSA (\( r = 0.870 \), \( P < 0.001 \)), but there was a significant improvement in this relationship (\( P < 0.001 \)) with a quadratic fit (Fig. 5). There was no

Figure 4
Left ventricular ejection fraction as a function of body surface area for patients with normal left hearts. There is a significant decrease in ejection fraction with increasing size over the range studied.
Left ventricular wall mass (LVM) also was linearly related to BSA ($r = 0.956, P < 0.001$; fig. 6). Values for LVM/BSA were not different for infants and older children, but LVM/weight was higher for infants while LVM/height was less for the infant age group (table 1). In table 2, the multiple regression equation relating LVM, height, and weight is given.

Left atrial maximal volume (LAMax) was linearly related to BSA ($r = 0.925, P < 0.001$; fig. 7). LAMax was significantly less in terms of LAMax/BSA and LAMax/height for infants than for older children (table 1). As with LVEDV, LAMax was significantly dependent on height, weight, and age (table 2). The equations for infants and older children again were significantly different ($P < 0.001$) in terms of residual difference between observed and predicted LAMax.

Discussion

Because of the increasing use of left heart volume determinations in evaluating myocardial performance, a reappraisal of methodology and normal values was undertaken with particular emphasis on the obtainable accuracy and reliability of these measurements in the small hearts of young infants. The

significant difference in LVSO/BSA between infants and older children (table 1).

The most significant multiple regression analysis was found using height, weight, and (weight)$^2$ as independent variables (table 2). The equation relating height, weight, and LVSO was not different for infants and older children.

Figure 5

Left ventricular systolic output as a function of body surface area. This relationship is exponential over the range studied.

Figure 6

Left ventricular wall mass as a function of body surface area. The regression equation ±10 and 20% of predicted values is shown.

Figure 7

Left atrial maximal volume as a function of body surface area. The regression equation ±10 and 20% of predicted values is shown.

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portmortem studies showed that with the use of a separate regression equation relating calculated and true volumes for left ventricles <15 cm³ and those >15 cm³, an average residual error of only 0.5 cm³ or 12.7% was obtained in the small hearts and 2.4 cm³ or 9.3% in the larger hearts.

When these new regression equations were applied to data obtained from 56 patients with normal left hearts, the values normalized for size for LV end-diastolic volume were significantly less for infants (< 2 years) than for older children, with the absolute values showing no significant change from previously published data.¹

The ejection fraction also remained significantly greater for infants than for older children, but the absolute value for infants (68%) was not as high as that previously reported (76%).¹ The explanation for the reduced value for the infant ejection fraction lies in the previous regression equation used to correct calculated volumes (V' = 0.393V - 2.0 cm³). This equation subtracts 2 cm³ from all calculated volumes and, thus, has a greater relative effect on end-systolic than end-diastolic volume. This difference becomes quite large at small end-diastolic volumes and, thus, in all likelihood, led to a falsely high ejection fraction when this equation was used.¹ The present equation for small volumes does not contain a constant (V' = 0.733V) and, thus, has a similar relative effect on diastolic and systolic volumes.

One obvious question that must be considered is whether or not the same regression equation should apply to both systolic and diastolic volumes. The relationship of the volumes of the postmortem hearts in this study to the volume range at which the patient's or animal's heart was operating during life cannot be defined precisely. The LVEDV for normal dogs has been reported as 2.1 cm³/kg body weight.⁹ Our values for normal LVEDV are 2.24 cm³/kg for infants less than 2 years and 2.84 cm³/kg for children above 2 years. Assuming ejection fractions of 65% in both animals and patients, normal left ventricular volumes can be estimated to range between 0.7 and 2.7 cm³/kg during a single cardiac cycle. The postmortem volumes in this study averaged 1.8 cm³/kg, and ranged from 0.3 to 5 cm³/kg, thus encompassing both systolic and diastolic values. In this regard, J. H. Gault, J. W. Covell, and J. Ross, Jr. (personal communication) have calculated cineangiographic volumes of dog left ventricular casts using the area-length method and found no difference in the relationship between known and calculated volumes for systolic versus diastolic casts.

The left atrial maximal volume (LAMax/BSA) also was significantly less for infants than for older children (26 ± 5 cm³/m² versus 38 ± 8 cm³/m²). The fact that no difference was found in this variable between these two groups in the previous study¹ is probably explainable by the small number of original observations in the infant age group.

The left ventricular mass (LVM/BSA) and left ventricular systolic output (LVSO/BSA) were not different for infants and older children, and average values were not significantly different from those previously published.¹

The abrupt change at 2 years in normal values for LVEDV, ejection fraction, and LAMax is, of course, an oversimplification. Indeed there were only four normal patients between the ages of 1 and 2, and 15 patients less than 1 year old. There was no patient under 1 year whose LVEDV/BSA value was within two standard deviations of the normal value for patients over 2 years. Thus, there appears to be clear separation between patients less than 1 and those more than 2 years. Of the four patients between 1 and 2 years, two (1.3 and 1.6 years) had values for LVEDV/BSA less than two standard deviations of the older patients' mean, and two (1.3 and 1.7 years) had values that were clearly within this range. Although more normal data are needed as to the transition in normal values in this age group, the present standards were found to be most useful with the age cutoff at 2 years.

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The use of body surface area as a means for normalizing data for patients of different size has received considerable criticism chiefly because of the probable inaccuracies in precise estimation of this variable. For this reason, multiple regression analysis was applied to the data obtained with height, weight, and age as independent variables. From these equations, predicted volumes can be calculated rapidly or derived with the use of the nomograms. By comparison of the observed and predicted values for any given patient, the percentage of normal for any of the volume variables can be calculated and compared with the 95% limits of normal as defined in this study (table 2).

The possible effects of contrast media on hemodynamics and ventricular volume determinations have been discussed previously in detail. The stability of left ventricular peak pressure, peak dP/dt, heart rate, and duplicate ventricular volume determinations in our laboratory during the initial levogam phase of pulmonary artery cines has been demonstrated. In addition, the excellent correlation between Fick and/or dye outputs versus angiographic outputs has been shown repeatedly.

The normal values for older children for left ventricular volume, mass, and ejection fractions agree well with those of Kennedy et al. for adults. The LVEDV/BSA values are somewhat less than those obtained by Miller and Swan in children, but the ejection fractions are similar. The latter authors' use of a method of volume calculation yielding a slightly high absolute value for LV volume explains this discrepancy. The value for LAMax/BSA found in this study for children (38 ± 8 cm$^3$/m$^2$) is also in good agreement with that found by Murray et al. (35 ± 8.7 cm$^3$/m$^2$) in normal adults. These values are somewhat higher than those reported by Miller and Swan in children (24 ± 4.8 cm$^3$/m$^2$).

Possible explanations for the smaller left ventricular and left atrial volumes in infants have been discussed previously. The more rapid heart rates in infants remains the most plausible explanation for this phenomenon with the relative curtailment of late diastolic filling. An increase in myocardial contractile state in infants versus older children either secondary to a greater sympathetic influence (or lesser parasympathetic influence) or the more rapid heart rate per se could also influence end-diastolic size and ejection fraction. Another possible factor is an alteration in compliance with age as indicated by the finding in animals of increased ventricular distensibility after the perinatal period.

The purpose of this investigation was to assess the ability to estimate small left heart volumes and to provide standards of normalcy for use in evaluating left heart size and performance in children with heart disease. The nomograms provided allow the rapid estimation of predicted values given a patient's height, weight, and age. By a comparison of observed and predicted values, a statement can then be made as to whether or not a patient falls within 95% limits in regard to the variable(s) in question. It is projected that this method will allow a more critical evaluation of an individual patient's myocardial response to his congenital or acquired cardiac lesion.

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