Right Ventricular Volume Determinations in Children

Normal Values and Observations with Volume or Pressure Overload

By Thomas P. Graham, Jr., M.D., Jay M. Jarmakani, M.D., Gerald F. Atwood, M.D., and Ramon V. Canent, Jr., M.D.

SUMMARY
Right ventricular (RV) volumes were calculated from biplane cineangiograms in 46 patients undergoing diagnostic cardiac catheterization. Validation of methodology was performed by comparison of known and calculated volumes of postmortem RV casts as well as by comparison of cineangiographic RV and left ventricular (LV) stroke volumes of patients without shunts or valvular insufficiency. Seven infants, <1 year of age, with normal right hearts as compared with older children showed smaller RV end-diastolic volumes (39 ± 8 vs 70 ± 13 ml/m², P < 0.001) as well as decreased RV systolic indices (SI) (3.71 ± 0.68 vs 4.66 ± 1.10 liters/min/m², P < 0.05). There were no differences between normal infants and older children for RV ejection fraction (EF), RVEDV/LVEDV = 1.01, RVSI/LVSI = 0.99, and RVEF/LVEF = 1.04 vs 0.99. In 13 patients with isolated pulmonary stenosis, RVEDV, RVF, RVSI, RVEDV/LVEDV, and RVSI/LVSI were not different from normal, but RVEF/LVEF averaged 1.13 vs 0.99 in normal infants, P < 0.05. In contrast, 11 patients studied with atrial septal defect or total anomalous pulmonary venous connection had significant increases in RVEDV (126 ml/m²), RVSI (9.34 liters/min/m²), RVEDV/LVEDV (2.36), RVSI/LVSI (2.81), and RVEF/LVEF (1.17), but normal values for RVEF. There was a significant linear relationship between Qs/Qp from oxygen data and RVSI/LVSI. In three patients studied an average of 1 year following atrial septal defect (ASD) repair, RVEDV remained elevated. In volume overload, alterations in RV volume characteristics are apparent and can be useful in shunt estimation; adaptation to an RV pressure overload, however, is not associated with detectable volume alterations.

Additional Indexing Words:
Congenital heart disease  Atrial septal defect Right and left heart volume comparisons

Angiocardiographic estimation of left ventricular volume in man has become an established procedure in many cardiovascular laboratories, and the clinical uses of such data are well known. In contrast, angiocardiographic estimation of right ventricular volume has not been applied clinically. The more complex internal geometry of the right ventricle (RV) when compared with the left ventricle (LV) undoubtedly has contributed to the reluctance of investigators to pursue RV volume estimation.

Several recent reports, comparing known and calculated angiocardiographic volumes of postmortem human and dog casts, have indicated the accuracy of this method is comparable to that of LV volume estimation. In addition, in vivo studies in both man and dogs comparing angio- graphic RV stroke volume with LV stroke volume or with flowmeter determinations of RV stroke volume have shown a good correlation between these variables.

The purpose of this investigation, therefore, was to develop a method for cineangiographic RV volume estimation in infants and children using postmortem RV casts, to test the model with in vivo comparisons of RV and LV stroke volumes in children without shunts or valvular insufficiency, to develop normal standards for RV end-diastolic volume, end-systolic volume, and ejection fraction in infants and children with normal right hearts,
and finally to apply these standards to the study of RV volume characteristics in patients with isolated volume or pressure overload of the right heart.

Methods

In Vitro Right Ventricular Cast Studies

Vinyl rubber casts were made of right ventricles from patients with normal right hearts undergoing postmortem examination. Liquid, room-temperature vulcanizing silicone rubber (RTV-11, General Electric Co.) was used to fill the right heart prior to fixation by clamping the inferior vena caval orifice of the right atrium and filling the heart through the superior vena cava. The hearts were filled with the silicone rubber at a filling pressure of approximately 12 cm H₂O while suspended in 90% formalin. The filling pressure was estimated by the height of the liquid silicone rubber column above the middle of the right ventricle (approximately 10 cm) multiplied by the specific gravity of the liquid (1.235 g/cm³). The cast was made radiopaque by mixing a small amount of barium sulfate with the liquid rubber. After 12 hours, the vulcanized cast was removed from the heart and the right ventricular

Figure 1

Biplane cineangiocardiograms of postmortem human right ventricular casts.
portion cut away from the remainder of the cast at the tricuspid and pulmonary valves. The real volume (V) of each cast was determined by water displacement.

Biplane cineangiocardiograms of the casts were exposed with the cast in the estimated anterior-posterior (AP) and lateral (Lat) projections which the right ventricle would have occupied in vivo (fig. 1). For calibration purposes, a grid of 625 squares of fine steel wire 1 cm x 1 cm each embedded in Plexiglass was filmed perpendicular to the AP and Lat X-ray tubes at the position the cast occupied. The films of the grid were used to correct for X-ray magnification.

The films of the casts were projected onto a drawing board, and the images were outlined by hand. Three different models were used to calculate the volume of the casts.

Model 1: Simpson’s Rule. In this model the AP and Lat images were divided into 10 equal parts using 11 horizontal lines. The cross section of the RV when viewed from above was assumed to be an ellipse, the volume of each segment was calculated, and the volume of the segments were summed using Simpson’s rule as illustrated in figure 2. In addition, the images were divided into 20 and 50 equal parts and the volumes calculated in the same manner in order to determine if a greater number of divisions would increase the accuracy of the method.

Model 2: Two-Chamber Method. The second model uses only the lateral view of the RV. On this view, there is a clear separation at the superior aspect of the tricuspid valve between outflow tract or infundibulum above and inflow tract or RV body below. The outflow tract is generally cylindrical and the RV body more ellipsoidal. The RV body and outflow tract were separated by drawing a line from the most superior aspect of the tricuspid valve straight across the outflow tract parallel to the pulmonary valve annulus (fig. 3). The volume of the infundibulum was calculated assuming it to be a cylinder: \( V_0 = \pi r_0^2 h \) where \( V_0 \) = volume of outflow tract; \( r_0 \) = radius of the outflow tract measured at its midpoint; and \( h \) = height or length of the outflow tract. The volume of the body was calculated assuming an ellipsoid of revolution: \( V_i = 4/3\pi r_i^2 \) (LL/2) where \( V_i \) = inflow tract or RV body volume; \( r_i \) = radius of the ellipsoid; and LL = the length of the ellipse. The longest length was measured directly, and the radius was calculated as \( r_i = 2A/\pi LL \) where A = the area of the RV body. The total RV volume then equals \( V_i + V_o \).

Model 3: Area-Length Method. The third model uses biplane images, and the entire RV is assumed to be an ellipsoid of revolution with volume \( V = 4/3\pi r(AP) \times r(Lat) \times LL/2 \) where \( r(AP) \) = the radius calculated from the AP view and \( r(Lat) \) = the radius calculated from the lateral view as described above.

\[
\text{Figure 2}
\]

Simpson’s rule method of right ventricular volume calculations.
Figure 3

Two-chamber method of right ventricular volume calculations.

Regression analysis was used to relate water displacement volumes (V) and calculated volumes (V) to determine the model(s) which can be used to estimate RV volume most accurately. The regression equation(s) thus derived were used to correct calculated in vivo right ventricular volumes.

In Vivo Right Ventricular Volume Studies

Right ventricular volume determinations were performed via biplane cineangiograms obtained during routine diagnostic cardiac catheterization in 33 infants and children. For this study, patients were selected whose right ventricular output would be expected to equal the left ventricular output in order to provide a means for in vivo determination of the accuracy of the volume calculations. Thus, patients with intracardiac shunts or valvular regurgitation were eliminated.

Diagnoses included 16 patients with normal right hearts (table 1), 13 patients with pressure overload secondary to pulmonary stenosis with a right ventricular-to-pulmonary artery gradient of ≥ 30 mm Hg, three patients studied following Mustard's correction of transposition of the great arteries, and one patient with a cerebral A-V fistula. All patients in the normal group had normal values for left ventricular end-diastolic volume, ejection fraction, and end-diastolic pressure (≤ 12 mm Hg). Two patients in the normal group have minimal pulmonary stenosis with a right ventricular-to-pulmonary artery pressure gradient of ≤ 10 mm Hg. One patient had intermittent paroxysmal supraventricular tachycardia of short duration. He had never had prolonged tachycardia or symptoms of heart failure. He was in sinus rhythm at the time of the study. One patient was studied 6 months after ligation of an anomalous conus coronary artery arising from the pulmonary artery. He was asymptomatic with normal preoperative and postoperative electrocardiograms.

In the pulmonary stenosis group, ages ranged from 4 days to 6 years and peak right ventricular pressure ranged from 55 to 160 mm Hg with a mean value of 92 mm Hg. Patients less than 12 months were studied with intramuscular meperidine (1–1.5 mg/kg) and/or promethazine (0.5–0.7 mg/kg) sedation; patients above 12 months were studied with light general anesthesia using nitrous oxide and small amounts of halothane (≤ 0.5%) or with intramuscular Innovar 0.025 cc/kg (a combination of droperidol 2.5 mg/cc and fentanyl 0.05 mg/cc). Twenty of these patients were studied at Duke University and 13 at Vanderbilt University.

Biplane cineangiograms (AP and lateral) of the right ventricle were obtained at 60 frames/sec following the injection of 1–1.25 ml/kg of 75% sodium and meglumine diatrizoates (Hypaque M, Winthrop Laboratories) into the right ventricle or right atrium. Right ventricular images were projected onto a drawing board and end-diastolic and end-systolic frames were drawn. In the patients studied at Vanderbilt, projected images were digitized directly from a digitizing table onto magnetic tape for processing. In a similar manner, left ventricular end-diastolic and end-systolic frames were drawn during the levogram phase of the cine. The electrocardiogram was monitored during the cine, and all ectopic and postectopic beats were excluded from analysis. In addition, if the heart rate during the levogram phase was different by more than 10/min from that during the right heart phase, the data were not used. A grid system filmed at the end of each study was used to correct for image magnification. The details of this system for left heart volume calculations has been presented previously.8 Left ventricular volumes were calculated using the area-length method9 with appropriate regression equation correction of calculated volumes.10 Left ventricular end-diastolic volume (LVEDV), LV end-systolic volumes (LVESV), LV stroke volume = LVSV = LVEDV – LVESV, LV systolic output = LVSV × heart rate, and LV ejection fraction = LVEF = LVSV/LVEDV were calculated for each patient.

Right ventricular volumes were calculated by the three methods described for the cast studies. Right ventricular end-diastolic volume (RVEDV), RV end-systolic volume (RVESV), RV stroke volume (RVSV), RV systolic output (RVS0), and RV ejection fraction (RVEF) were derived for each patient as described above the the LV calculations.

For the normal group, regression analysis was performed on RVEDV as a function of BSA, height, weight, age, and heart rate both as single independent variables and in multiple regressions analysis. Linear (y = ax + b), parabolic (y = ax² + bx + c), and exponential (y = axᵇ) curve fitting were applied to the data.

The final group of patients studied was the volume-overload group in whom RV output would be expected to exceed LV output. This group included seven patients with a secundum atrial septal defect and three patients with total anomalous pulmonary venous connection. Ages ranged from 4 months to 11 years, and Q/V/Q, by oxygen washout data ranged from 1.8 to 3.6. In addition, three patients were studied following ASD repair. Five patients were studied at Vanderbilt and nine at Duke.
## Table 1

### Right Ventricular Volumes for Patients with Normal Right Hearts

| Pt | Age | BSA (m²) | HR (beats/min) | RVP (mm Hg) | RVEDV (ml/m²) | RVEF (RVSV/RVEDV) | RVSI (liters/min/m²) | RVEDV/LVEDV | RVEF/LVEF | RVSI/LVSI | Diagnosis                  |
|----|-----|----------|---------------|-------------|--------------|----------------|--------------------|----------------|------------|-----------|-------------|-----------------------------|
| 1.  | O.A. | 2 days   | 0.21          | 150         | 43/6         | 31             | 0.69               | 3.146         | 0.81       | 1.10      | 0.88        | PPS                          |
| 2.  | W.H. | 4 days   | 0.24          | 143         | 45/5         | 48             | 0.58               | 4.000         | 1.25       | 0.90      | 1.12        | VPS                          |
| 3.  | L.Y. | 11 days  | 0.14          | 150         | 25/3         | 49             | 0.78               | 4.530         | 1.61       | 1.28      | 1.61        | Normal                       |
| 4.  | J.B. | 4 mo     | 0.29          | 146         | 45/6         | 30             | 0.67               | 3.058         | 0.71       | 1.00      | 0.72        | PPS                          |
| 5.  | D.W. | 5 mo     | 0.44          | 113         | 18/5         | 40             | 0.55               | 2.476         | 0.91       | 1.06      | 1.04        | Sys hypertension             |
| 6.  | M.S. | 5 mo     | 0.32          | 140         | 36/8         | 44             | 0.66               | 4.046         | 1.04       | 0.94      | 0.97        | Sys hypertension             |
| 7.  | M.W. | 11 mo    | 0.38          | 150         | 26/4         | 30             | 0.67               | 3.060         | 0.71       | 1.00      | 0.72        | Bicuspid Ao valve            |

### P value (2A vs 2B)

<table>
<thead>
<tr>
<th>Group 2A: Age &lt; 1 year</th>
<th>Group 2B: Age &gt; 1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>142</td>
</tr>
<tr>
<td>SD</td>
<td>±12</td>
</tr>
<tr>
<td>P value (2A vs 2B)</td>
<td>&lt;0.010</td>
</tr>
</tbody>
</table>

### Abbreviations:
- RVP = right ventricular pressure
- EDV = end-diastolic volume
- EF = ejection fraction
- SI = systolic index
- SI = cardiac index
- LV = left ventricular
- PPS = peripheral pulmonary stenosis
- VPS = valvular pulmonary stenosis
- Sys = systemic
- Ao = aortic
RV VOLUMES IN CHILDREN

In Vivo Volume Studies

Comparison of RV and LV Stroke Volumes

A graphic comparison of right and left ventricular stroke volumes for all patients is shown in figure 5. In this comparison, RV volumes were calculated using Simpson's rule. The correlation coefficient, 0.971, and the regression equation demonstrate the close agreement between the two variables. In table 3, a comparison of RV and LV stroke volumes for all three methods of RV volume estimation is given. Again, as for the cast studies, the Simpson's rule method statistically provided the closest agreement between RV and LV stroke volume. Therefore, the remainder of the results will be for RV volumes calculated by the Simpson's rule method.

Normal Values for RV Volumes

In table 1, right and left ventricular volume data for patients with normal right hearts are presented. Right ventricular end-diastolic volume (RVEDV) values are quite similar to LV end-diastolic volumes (LVEDV) with the average RVEDV/LVEDV ratio equal to 1.01. The seven infants less than 1 year of age have smaller normalized end-diastolic volumes (ED/BSA) than older children, as well as more rapid heart rates. The average value for RVEDV/BSA for infants was 39 ± 8 (± ± sd) ml/m² while for older children RVEDV averaged 70 ± 13 ml/m². Right ventricular end-diastolic volume as a function of BSA is shown graphically for the normal patients in figure 6. This relationship was fit by the exponential curve shown with RVEDV = 64.2 (BSA)^1.34. An equally good exponential fit was obtained with RVEDV as a function of height in centimeters [RVEDV = 0.00086 (ht)^2.31, P < 0.001, r = 0.975], or as a function of weight in kilograms [RVEDV = 2.45 (wt)^0.978, P < 0.001, r = 0.959]. In applying these exponential equations to the pulmonary stenosis and atrial septal defect patients, there was no significant difference (P > 0.5) in the predicted normal values.

Table 2

<table>
<thead>
<tr>
<th>Method</th>
<th>Volume</th>
<th>see</th>
<th>P</th>
<th>r</th>
<th>Av error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Simpson's rule</td>
<td>V' = 0.649V</td>
<td>6.73</td>
<td>&lt;0.001</td>
<td>0.992</td>
<td>12.3</td>
</tr>
<tr>
<td>2. Area-length</td>
<td>V' = 0.680V</td>
<td>8.03</td>
<td>&lt;0.001</td>
<td>0.989</td>
<td>14.7</td>
</tr>
<tr>
<td>3. Two-chamber</td>
<td>V' = 0.712V</td>
<td>8.77</td>
<td>&lt;0.001</td>
<td>0.988</td>
<td>16.6</td>
</tr>
</tbody>
</table>

Abbreviations: V' = volume measured by water displacement; V = calculated volume; see = standard error of the estimate; av error = V' - V × 100 (%).

Circulation, Volume XLVII, January 1973
for RVEDV whether or not BSA, height, or weight was used as the independent variable. Separate curves for infants versus older children were not significantly different. In addition, multiple regression equations relating RVEDV to height, weight, age, and HR did not improve the fit.

Right ventricular ejection fraction (RVEF) averaged 0.66 in infants and 0.64 in older children. This difference was not significant. The ratio of RVEF/LVEF was 1.04 in infants and 0.99 in older children (P > 0.3).

The RV systolic index (RVSI) was 3.71 liters/min/m² in infants versus 4.66 liters/min/m² in older children (P < 0.05). The ratio RVSI/LVSI averaged 1.01 in both groups.

Pulmonary Stenosis

Right ventricular EDV, RVEF, RVSI, RVEDV/LVEDV, and RVSI/LVSI were not significantly different from normal in patients with pulmonary stenosis (fig. 7). The ratio RVEF/LVEF was higher than normal (1.13 vs 0.99, P < 0.05). In patients older than 1 year of age, RVEDV averaged 60 ml/m² (P > 0.1) with RVEDV/LVEDV = 0.84, (P < 0.05). Despite large increases in peak systolic pressure (four patients with RVP = 100 mm Hg), there was no evidence of RV enlargement.

Atrial Septal Defect and Total Anomalous Pulmonary Venous Connection

All 11 preoperative patients had increases in RVEDV/BSA, RVSI, RVEDV/LVEDV, RVSI/LVSI, and RVEF/LVSI (fig. 8). The ejection fraction was normal. The ratio of RVSI/LVSI showed a significant linear correlation with Qp/Qs estimated from oxygen data (P < 0.05, r = 0.688).

In three patients catheterized 1 year following successful ASD repair, RVEDV/BSA remained increased while RVSI was normal. One patient had

Table 3

<table>
<thead>
<tr>
<th>Method</th>
<th>RSVV</th>
<th>se</th>
<th>P</th>
<th>r</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Simpson’s rule</td>
<td>0.958</td>
<td>4.47</td>
<td>&lt;0.001</td>
<td>0.971</td>
<td>P &gt; 0.5</td>
</tr>
<tr>
<td>2. Area-length</td>
<td>0.991</td>
<td>5.09</td>
<td>&lt;0.001</td>
<td>0.963</td>
<td>P &gt; 0.5</td>
</tr>
<tr>
<td>3. Two-chamber</td>
<td>0.712</td>
<td>10.20</td>
<td>&lt;0.001</td>
<td>0.853</td>
<td>P &gt; 0.2</td>
</tr>
</tbody>
</table>

Abbreviation: ANOVA = analysis of variance with comparison of RSVV versus LVSV using Student’s t test.

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a depressed ejection fraction but maintained a normal output with the elevated RVEDV.

Discussion

Both the in vitro cast studies and the patient investigations correlating right and left ventricular outputs derived from volume calculations indicate that right ventricular volume determinations can be performed from diagnostic cineangiograms with a reasonable degree of accuracy over a wide age range and with various hemodynamic abnormalities. The average error of 11–12% for the cast studies is similar to that found for the left ventricle and is in the error range of nearly all available methods for volume and/or flow quantitation.

The methodology for accurate right ventricular volume determinations requires particular attention to several details of data collection and analysis. Both right ventricular and right atrial injections of contrast media have been used. Although right ventricular injections alleviate any difficulties with recognition of right atrial-right ventricular overlapping borders, the frequency of premature ventricular beats is quite high. Careful positioning of a side hole (NIH) catheter in the midportion (in both AP and Lat projections) of the right ventricular inflow tract and relatively slow injection of 1 cc/kg of contrast media over 1 sec in infants and over 1.5–2 sec in older children will reduce the incidence of premature contractions. Right atrial contrast injections give a low incidence of premature contractions, but one is left with overlapping chamber borders. When the right ventricle is at end-diastole and thus right atrial volume is minimal, the recognition of the right ventricular borders is not difficult. However, at right ventricular end-systole, right atrial volume is maximal and border recognition is much more difficult. If the cines are of high contrast, right ventricular end-systolic borders can be defined by repeated cine replay of the entire cardiac cycle to enhance border recognition. A further aid in border recognition is the fact that the maximum vertical extent of the right ventricle (most caudad part of the RV to the uppermost part of the pulmonary annulus) must be the same in both views after correction for any differential X-ray magnification. The pulmonary annulus normally is visualized quite easily in the lateral view, but because of its position it is not recognizable on the AP view. With the use of the vertical extent of the RV as seen in the lateral view, the true AP vertical extent can be easily approximated.
Another difficult aspect of RV border recognition is the trabeculated left border in the anterior-posterior view (fig. 1). We have chosen to include the entire trabeculated border of the RV in the image. Thus, the image includes a significant amount of trabeculated RV as well as papillary muscles, and a regression equation is essential for volume estimation.

All three methods of volume estimation showed reasonable correlations between measured and calculated volume. The method using Simpson's rule showed the smallest error in volume estimation. All methods consistently overestimated volume by 30 to 35%. This overestimation is undoubtedly secondary to the inclusion of RV muscle in the image as described above, as well as to the fact that the RV body when viewed from above is not ellipsoidal in shape for the most part, but actually more crescent shaped or equal to one half an ellipse. Again, the use of a regression equation partially corrects for these problems.

The patient studies indicate that, as with the left ventricle, infants show a smaller normalized end-diastolic volume than older children. This difference is probably related to the more rapid heart rate in infants as has been suggested previously. The RV ejection fraction was not higher in infants as was found for the LV. This lack of a difference may be related to the relatively small patient groups.

The ratio RVEDV/LVEDV was 1.01 for the normal group. Arcilla et al. found a somewhat larger RV than LV in eight patients with normal right hearts using a somewhat different method.

The application of regression equations for defining normal standards for left ventricular volume variables has been useful in our patient population. For the right ventricle, a single exponential curve relating RV end-diastolic volume to BSA appears to adequately predict normal values for this variable for both infants and older children (fig. 6). Because of the difficulty in completely accurate BSA estimation in infants, body height or weight may be used for this purpose also. The application of this method for defining normal limits for RVEDV is illustrated in table 4 (see also fig. 6).

Patients with an isolated pressure overload in the form of pulmonary stenosis did not show significant changes from normal in RV end-diastolic volume, nor in RV ejection fraction. None of these patients had clinical evidence of congestive failure. The small hearts and normal ejection fraction and RV outputs indicate adequate myocardial compensation in these patients probably secondary to increased muscle mass. In children with aortic stenosis, left ventricular end-diastolic volumes were found to be diminished and ejection fractions actually increased. A similar trend is present in the PS patients for the RV, with RVEDV/LVEDV significantly decreased from normal in patients older than 1 year and RVEF/LVEF increased for the entire group.

Patients with atrial septal defects or total anomalous pulmonary venous connection showed large increases in all RV volume variables measured with the exception of the ejection fraction which was normal. This method provides a means for pulmonary blood flow estimation (RVSI) as well as degree of left-to-right shunting (RVSI/LVSI). An accurate estimation of pulmonary flow in patients with large ASDs or TAPVC can be very difficult from oxygen determinations alone, and thus right and left heart volumes can be quite useful in shunt estimation.

The finding of increased RV volumes in three patients catheterized 1 year postoperatively as part of a cooperative study has a parallel in a previous study showing increased LV volume in postoperative ventricular septal defect patients studied an average of 2 years following repair. These investigations suggest that changes in filling characteristics of the ventricle can occur with chronic volume overload which are not completely reversible in 1–2 years following correction. The possibility also exists that a depression in myocardial contractile state which can accompany chronic hypertrophy secondary to volume overload may be a factor in the chronic elevation of end-diastolic volume.

### Table 4

**Regression Equations for Prediction of Normal Values for Right Ventricular End-Diastolic Volume**

| Predicted: |
|------------------|------------------|
| RVEDV (ml) = 64.2 BSA \(^{1-34} \text{(m}^2\) |
| or |
| RVEDV (ml) = 0.00086 ht \(^{1-31} \text{(cm) } |

**Example:**

- Pt L.S.; age 6 mo; Dx ASD; BSA 0.30m\(^2\); ht 63.5 cm
- Predicted RVEDV from BSA = 12.7 ml
- Predicted RVEDV from ht = 12.6 ml
- Observed RVEDV = 22.1 ml
- Obs/pred \(\times 100 = 22.1/12.7 \times 100 = 174\%\) of normal
- 90% confidence limits for BSA of 0.30 m\(^2\) are 11 and 16 m
Acknowledgments

The authors gratefully acknowledge the work of Mrs. Marilyn Plunkett, Mr. Ron Price, Mrs. Martha Mason, and Mrs. Ida Phialas for their aid in data processing, as well as the work of Mrs. Merrily Gibson in preparation of this manuscript.

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_Circulation_. 1973;47:144-153
doi: 10.1161/01.CIR.47.1.144
_Circulation_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

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