Radionuclide Ventriculography for Assessment of Absolute Right and Left Ventricular Volumes in Children

MARK D. PARRISH, M.D., THOMAS P. GRAHAM, JR., M.D., MARK L. BORN, M.D., JERRY P. JONES, PH.D., ROBERT J. BOUCEK, JR., M.D., AND C. LEON PARTAIN, PH.D., M.D.

SUMMARY We determined absolute right and left ventricular volumes and cardiac output from the equilibrium radionuclide angiogram in 26 children, ages 3 months to 18 years, with diverse types of heart disease. We validated these results by comparing them with left ventricular (20 patients) and right ventricular (16 patients) cineangiographic volumes and cardiac output. Radionuclide volumes and cardiac outputs were determined in two ways: by a geometric method (area-length for left ventricle, Simpson’s rule for right ventricle) and by a count-based method (correcting ventricular regional counts for frame duration, acquisition time, venous blood counts and attenuation). Both methods for estimating left ventricular end-diastolic volume compared favorably with cineangiography (correlation coefficients greater than 0.90). The count-based method also correlated well for the right ventricle. End-systolic measurements were not possible. Count-based assessment of cardiac output also correlated well with cineangiographic values. We conclude that right and left ventricular volumes and cardiac output can be reliably measured in children with equilibrium radionuclide ventriculography.

EQUILIBRIUM radionuclide ventriculography is a useful noninvasive method for assessing ventricular volumes and cardiac output. Although use of this technique to determine left ventricular volumes and outputs has been validated in adults,\textsuperscript{1-10} it has not been investigated in children. Several investigators have attempted to validate the radionuclide determination of the right ventricular ejection fraction,\textsuperscript{11-13} but only Hooper et al.\textsuperscript{14} examined right ventricular volumes by this technique. For these reasons, we now report our experience with the radionuclide determination of right and left ventricular volumes and outputs in children. We determined volumes from radionuclide studies using a count-based method\textsuperscript{1-6} and a geometric method\textsuperscript{7-10} and compared the results with cineangiographically determined volumes and cardiac outputs.

Materials and Methods

Between January 1981 and June 1981, we performed radionuclide ventriculography in 26 children, ages 3 months to 18 years (mean 8 years), within 1 week of diagnostic cardiac catheterization. The patients had diverse types of heart disease (table 1). Informed consent was obtained before the radionuclide studies were performed.

Multiple-gated equilibrium radionuclide studies were performed at rest with the patients supine. Red blood cells were labeled in vivo with technetium-99m;\textsuperscript{15} the adult dose of 20 mCi was adjusted downward for children based on their body surface area.\textsuperscript{16} The cardiac blood pool was imaged with a single-crystal mobile gamma camera (Picker Dyna-Mo) interfaced to a dedicated GAMMA-11 computer system (Digital Equipment Corporation). We used either an all-purpose or a high-resolution collimator. The camera head was oriented to maximize ventricular separation. This was usually accomplished with a 30–80° left anterior oblique orientation with 10–15° of caudal tilt.

The cardiac blood pool was imaged for 5 minutes; 1–2 million total counts were obtained. We used 40-msec frame durations for heart rates less than 100 beats/min and 30-msec frame durations for rates greater than 100 beats/min. Within 15 minutes of completing the left anterior oblique collection, 5 ml of blood were withdrawn in a standard 6-ml syringe, and placed directly on the camera head with the collimator still in place. The activity in the syringe was counted for 10 minutes to estimate red blood cell labeling (counts/ml/sec).

To correct ventricular activity for attenuation by the chest wall, the thickness of the chest wall must be assessed. A 5-minute collection was obtained with the camera head in the 30° right anterior oblique position. A 5-cm lead marker was placed in the field of view for distance calibration, and a technetium marker was placed on the patient’s chest at the cardiac apex. Then, the chest wall thickness (cm) was estimated by measuring the distance from the midportion of the cardiac silhouette to the point source on the patient’s chest wall. No angular correction was made. However, because of inherent inaccuracies in this method, we simplified our protocol by eliminating this determination. Figure 1 displays the linear correlation between the patient’s body surface area and chest wall thickness measured from the radionuclide image ($r = 0.93$). The patients used for this correlation weighed 6–69 kg (0.36–1.9 m$^3$). We used the equation from this linear relationship ($y = 3.7x + 3.6$) to determine an assumed chest wall thickness for each patient. We then recalculated our ventricular volumes using the assumed chest wall thickness in the attenuation correction.

From the Division of Pediatric Cardiology, Department of Pediatrics, and the Division of Nuclear Medicine, Department of Radiology, Vanderbilt University Medical Center, Nashville, Tennessee.

Supported by the Tennessee Heart Association, Nashville, Tennessee.

Address for correspondence: Mark D. Parrish, M.D., Department of Pediatric Cardiology, Vanderbilt University Medical Center, Nashville, Tennessee 37232.

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All radionuclide studies were analyzed to obtain right and left ventricular volumes. A method similar to that described by Maddahi et al.11 was used. The right and left ventricular regions were outlined by hand at end-diastole and end-systole using a joystick on a 64 × 64-pixel matrix (fig. 2). Since the limit of the left ventricular outflow tract may be the most difficult portion of this region to identify, the superior lateral portion of the region was connected by a straight line to the most superiorly visualized portion of the ventricular septum (fig. 2, line ab). The right ventricular medial and lateral borders were easily identified in a similar fashion. Two segments of the right ventricular region may be more difficult to define: the right ventricular outflow tract and the right ventricular–right atrial border. For purposes of standardization, the right ventricular outflow tract was identified at the same level as the most superior portion of the left ventricular region (fig. 2, point c). This line was then extended laterally to the superolateral border of the right ventricle (line cd). The remainder of the lateral border was drawn as it was for the left ventricle. When a clear separation of right ventricle from the right atrium was seen, the right atrial region was excluded from the ventricular outline (fig. 2, line de). However, in some end-diastolic and end-systolic images, no distinct right atrial demarcation could be seen. When this occurred, the entire lateral border was included in the right ventricular outline. A small region for background correction, encompassing 10–20 pixels, was drawn on the end-systolic frame, 2–4 pixel widths lateral to the left ventricle, thereby avoiding aortic and splenic activity. Endless-loop playbacks of the cardiac cycle viewed before the ventricular regions were drawn helped considerably in identifying the right ventricular–right atrial border.

Ventricular volumes were calculated from the radionuclide studies by two techniques, a count-based method and a geometric method. Two formulas were used for the count-based estimation of ventricular volume. The regional counts were first corrected for background activity.

\[
\text{Background-corrected regional counts (Frame duration × collected cycles × blood counts)}
\]

Formula 1 corrects the total number of counts in the ventricular region (right ventricle, left ventricle, end-diastole or end-systole) for the frame duration (sec) and the total number of collected cardiac cycles. This number was then converted to an actual volume (ml) by dividing by the venous blood activity (counts/ml/sec). Formula 2 further corrects this volume to account for attenuation of regional blood counts by the chest wall.17 The chest wall thickness (CWT) (cm) was mul-

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**Table 1. Patient Group**

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-transposition</td>
<td>6 patients (4 postop)</td>
</tr>
<tr>
<td>Aortic stenosis or aortic insufficiency</td>
<td>6 patients (1 postop)</td>
</tr>
<tr>
<td>Tetralogy of Fallot</td>
<td>4 patients (2 postop)</td>
</tr>
<tr>
<td>Cardiomyopathy</td>
<td>4 patients (0 postop)</td>
</tr>
<tr>
<td>Total anomalous pulmonary venous return</td>
<td>2 patients (0 postop)</td>
</tr>
<tr>
<td>Tricuspid atresia</td>
<td>2 patients (2 postop)</td>
</tr>
<tr>
<td>Ventricular tachycardia</td>
<td>1 patient (0 postop)</td>
</tr>
<tr>
<td>Atrioventricular canal</td>
<td>1 patient (1 postop)</td>
</tr>
<tr>
<td>Total</td>
<td>26 patients (10 postop)</td>
</tr>
</tbody>
</table>

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**Figure 1.** Comparison of patient's body surface area and estimated chest wall thickness.

**Figure 2.** End-diastolic and end-systolic radionuclide images showing the cardiac silhouette before and after region identification.
multiplied by an attenuation coefficient ($\mu$). The ventricular volume was then multiplied by the exponential of this number. We assumed the attenuation coefficient to be equal to 0.1.$^{18}$

End-diastolic volume (left anterior oblique projection) of both ventricles was estimated geometrically. End-systolic volumes were not determined geometrically because of the difficulties in accurately determining the end-systolic shape. The image size was calibrated with phantom grids before the ventricular volumes were determined. The following area-length formula was used to calculate left ventricular end-diastolic volume$^{19}$:

$$\frac{8}{3} \left( \frac{\text{area}^2}{\pi \times \text{longest axis}} \right)$$

(Simpson’s rule was used to estimate right ventricular volume.$^{16}$ The right ventricular region is divided into slices, and the volume of each slice is calculated. Insofar as only one projection is used, the slice width on the orthogonal view was assumed to be equal to the width on the left anterior oblique view.

The cardiac output of each chamber was calculated from geometric and count-based volumes using the formula

$$\text{EDV} \times \text{EF} \times \text{HR}$$

where EDV = end-diastolic volume, EF = ejection fraction, and HR = heart rate. In this calculation, ejection fraction is determined from end-diastolic and end-systolic images using the formula

$$\frac{(\text{EDC} - \text{BK}) - (\text{ESC} - \text{BK})}{\text{EDC} - \text{BK}}$$

where EDC = end-diastolic counts, ESC = end-systolic counts, and BK = background counts. Heart rate is taken as the average rate during the radionuclide collection.

From cineangiograms, right and left ventricular volumes were calculated using published methods. Volumes were calculated from biplane images for all patients, using the area-length method for the left ventricle$^{20}$ and Simpson’s rule for the right ventricle.$^{21}$

Twenty-five of 26 patients underwent left ventricular angiography within 1 week of radionuclide study. One patient was excluded from the radionuclide-cineangiographic comparison because the cineangiogram was inadequate and one was eliminated because the red blood cell labeling was inadequate; thus, 23 patients were available for comparison of left ventricular volumes. Blood samples were drawn from 20 of these 23 patients for determination of left ventricular volumes by the count-based method. Radionuclide playback images for volume determinations by the geometric method were available in 18 patients. Eighteen of 26 patients underwent right ventricular angiography within 1 week of radionuclide study. Again, because the cineangiogram and red blood cell labeling were inadequate in one patient each, 16 patients were available for radionuclide-cineangiographic volume comparisons with the count-based method. There were radionuclide images from 13 patients for comparison with geometrically determined right ventricular volumes.

Ventricular volumes were determined in five patients by both methods by one observer on two occasions (intraobserver variability). A second observer independently performed the region identification for the same five patients (interobserver variability). All observers were blinded to each other’s results, as well as to cineangiographic results.

Radionuclide volumes were statistically compared with cineangiographic volumes by linear regression analysis. Correlation coefficients for formulas 1 and 2 were compared by Fisher’s technique.$^{22}$ Intraobserver variation and interobserver variation were also analyzed by linear regression analysis of paired data from each patient. Statistical significance was defined as $p < 0.05$.

**Results**

The results of our intraobserver and interobserver correlations for both count-based and geometric determinations of ventricular volumes are presented in table 2. The count-based volumes were determined with a correction for attenuation (formula 2) and an assumed chest wall thickness. The left ventricular end-diastolic volumes calculated by the count-based method correlated well for both intraobserver and interobserver determinations, with correlation coefficient of 0.99 and mean absolute differences between observations (expressed as a percentage of observer 1’s first observation) of 2.6% (intraobserver) and 8.7% (interobserver). In addition, the left ventricular end-diastolic volumes calculated by the geometric method correlated well, with correlation coefficients of 0.99 and mean absolute differences between observations of 12.3% (intraobserver) and 7.9% (interobserver).

Determinations of right ventricular end-diastolic volumes were slightly less consistent. Although all correlation coefficients were 0.99, there were mean absolute differences for intraobserver determinations of 14.8% (count-based method) and 16.9% (geometric method). The interobserver differences were also slightly larger, i.e., mean absolute differences of 11% (count-based method) and 21.9% (geometric method).

Table 3 is a summary of the results of the radionuclide-cineangiographic comparisons for left ventricular volumes. Correlations were excellent for both the geometric method ($r = 0.97$) and the count-based method with attenuation correction ($r = 0.93$). Without attenuation correction, the correlation coefficient was significantly lower ($r = 0.86$).

Figure 3 shows the relationship between the radionuclide left ventricular volume and the cineangiographic volume. The absolute difference between the count-based estimate of left ventricular volume (assumed chest wall thickness) and the cineangiographic left ventricular volume was $30 \pm 5\%$ (mean $\pm$ SEM). This compares to an absolute difference between geometric determinations of radionuclide left ventricular volumes and cineangiographic left ventricular volumes...
TABLE 2. *Intraobserver and Interobserver Correlations and Differences: Ventricular Volumes*

<table>
<thead>
<tr>
<th></th>
<th>Mean absolute difference between observations†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
</tr>
</tbody>
</table>

**Intraobserver**
- Count-based*
  - Left ventricle: end-diastole: 0.99, 2.6%
  - Left ventricle: end-systole: 0.99, 16.7%
  - Right ventricle: end-diastole: 0.99, 14.8%
  - Right ventricle: end-systole: 0.99, 17.7%
- Geometric
  - Left ventricle: end-diastole: 0.99, 12.3%
  - Right ventricle: end-diastole: 0.99, 16.9%

**Interobserver**
- Count-based*
  - Left ventricle: end-diastole: 0.99, 8.7%
  - Left ventricle: end-systole: 0.99, 13.6%
  - Right ventricle: end-diastole: 0.99, 11.0%
  - Right ventricle: end-systole: 0.99, 17.0%
- Geometric
  - Left ventricle: end-diastole: 0.99, 7.9%
  - Right ventricle: end-diastole: 0.99, 21.9%

*Count-based method incorporates attenuation correction with an assumed chest wall thickness.
†Mean absolute difference expressed as a percent of observer 1's first determination.

Differences: Ventricular Volumes

of 20 ± 4%. The geometric end-diastolic volume comparisons are displayed in figure 4.

We also compared left ventricular outputs determined by the radionuclide technique with cineangiographic outputs (table 4). Although the additional variables of heart rate and ejection fraction were introduced, cardiac output determinations compared favorably for the left ventricle by both the geometric method (r = 0.87) and the count-based method (r = 0.87).

Table 5 summarizes the results of the radionuclide-cineangiographic comparisons for the right ventricle. Correlations of end-diastolic volumes were excellent for the count-based method both with and without attenuation correction (with attenuation correction r = 0.95). For the geometric method, the correlation coefficient was slightly lower (r = 0.87).

Figure 5 displays the radionuclide-cineangiographic correlation for the right ventricle at end-diastole using the count-based radionuclide technique. The mean absolute difference between the count-based estimate of

*Abbreviations: y = radionuclide volume; x = cineangiographic volume; n = number of patients; CWT = chest wall thickness.

TABLE 3. *Radionuclide-Cineangiographic Comparison of Left Ventricular Volumes*

<table>
<thead>
<tr>
<th>Technique</th>
<th>Time</th>
<th>r</th>
<th>SEE</th>
<th>Linear relationship</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form 1 (count-based: no attenuation correction)</td>
<td>End-diastole</td>
<td>0.86</td>
<td>± 12.8</td>
<td>y = 0.28x + 6.2</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>End-systole</td>
<td>0.93</td>
<td>± 5.3</td>
<td>y = 0.55x + 3.7</td>
<td>20</td>
</tr>
<tr>
<td>Form 2 (count-based: with attenuation correction and measured CWT)</td>
<td>End-diastole</td>
<td>0.94</td>
<td>± 22.4</td>
<td>y = 0.80x - 0.52</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>End-systole</td>
<td>0.98</td>
<td>± 8.5</td>
<td>y = 0.75x + 1.32</td>
<td>20</td>
</tr>
<tr>
<td>Form 3 (count-based: with attenuation correction and &quot;assumed&quot; CWT)</td>
<td>End-diastole</td>
<td>0.93</td>
<td>± 25.4</td>
<td>y = 0.79x + 0.23</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>End-systole</td>
<td>0.97</td>
<td>± 8.9</td>
<td>y = 0.70x + 2.6</td>
<td>20</td>
</tr>
<tr>
<td>Geometric</td>
<td>End-diastole</td>
<td>0.97</td>
<td>± 23.0</td>
<td>y = 1.1x - 14.3</td>
<td>18</td>
</tr>
</tbody>
</table>

*p < 0.05 for all determinations.

Figure 3. Comparison of radionuclide and cineangiographic left ventricular end-diastolic volume, using a count-based method with attenuation correction and assumed chest wall thickness for the radionuclide determination.
right ventricular volume and the cineangiographic right ventricular volumes was 30 ± 4%. This compares to an absolute difference between geometric determinations of radionuclide volumes of 34 ± 6%. The geometric end-diastolic comparisons are shown in figure 6.

We also compared right ventricular outputs determined by the radionuclide technique to cineangiographic outputs (table 4). The correlation coefficients for the right ventricle were lower than those for the left ventricle; the geometric method showed the poorest correlation coefficient \( r = 0.65 \). The correlation coefficient for the count-based method was slightly higher \( r = 0.79 \).

The effect of variable red blood cell labeling on our radionuclide cineangiographic correlation was examined (table 6). On average, our patients' blood samples showed a mean activity of 25 ± 3 counts/ml/sec. The radionuclide-cineangiographic ventricular volume correlations in our patients with blood counts less than 25 counts/ml/sec were 0.93 for the left ventricle and 0.97 for the right ventricle. In contrast, patients with blood counts ≥ 25 counts/ml/sec had correlation coefficients of 0.97 for the left ventricle and 0.85 for the right ventricle.

Patient size may be an important determinant of the accuracy of radionuclide volume determinations. The mean weight of our patients was 27 ± 4 kg. Table 7 displays the radionuclide-cineangiographic volume correlations for patients weighing less than 27 kg and for those weighing 27 kg or more. The correlation coefficients are excellent for patients of all sizes. For the smaller children, the count-based radionuclide method yielded correlation coefficients of 0.97 for the left ventricle and 0.90 for the right ventricle. For the larger children, the correlation coefficients were 0.88 for the left ventricle and 0.92 for the right ventricle.

Finally, we assessed the effect of changing from a high-resolution to a medium-resolution collimator in six patients in whom excellent radionuclide images were obtained. Each patient was imaged first with the high-resolution collimator and immediately thereafter with the medium-resolution (all-purpose) collimator. A venous blood sample was counted on each collimator. For estimation of left ventricular volumes, the mean difference between collimators was 1.9 ± 13.0% (± SD). For the right ventricle, the difference was 2.6 ± 12.4%. In both instances, the medium-resolution collimator gave a slightly higher estimate of ventricular volume.

### Discussion

Evaluation of ventricular volumes is extremely useful in the assessment of children with heart disease.23 However, validation of a noninvasive technique for determination of right and left ventricular volumes has not been reported.

Radionuclide assessment of left ventricular ejection fraction has been validated in adults by several groups. However, radionuclide determination of right ventricular ejection fractions has seldom been evaluated by cineangiographic correlations. Steele et al.24 found a correlation coefficient of 0.80 using the first-pass technique. Slutsky et al.12 compared the first-pass and equilibrium techniques for determination of right ventricular ejection fraction and found a correlation coefficient of 0.81. Hooper et al.14 compared equilibrium radionuclide ventriculograms with cineangiograms, and reported that correlation coefficients for the right ventricular ejection fraction varied from 0.28 to 0.84 (depending on the analysis technique); correlations for right ventricular volumes without attenuation correction ranged from 0.78 to 0.86. Our radionuclide-cineangiographic comparisons of right and left ventricular ejection fractions in children yielded correlation coefficients of 0.83 and 0.90, respectively.13

Silverman et al.25 compared left ventricular volumes determined by two-dimensional and M-mode echocardiography with cineangiographic volumes; the correlation coefficients were 0.97 and 0.83, respectively. These techniques, however, are difficult to apply to the assessment of the right ventricle, and may not be applicable in the exercising patient.

Four radionuclide methods for determining left ventricular volumes have been evaluated in adults: (1) a

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**Figure 4.** Comparison of radionuclide and cineangiographic left ventricular end-diastolic volume, using a geometric method for the radionuclide determination.

**Table 4.** Radionuclide-Cineangiographic Correlation Coefficients: Cardiac Output

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Method*</th>
<th>( r )</th>
<th>( SEE )</th>
<th>Linear relationship</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left ventricle</td>
<td>Geometric</td>
<td>0.87 ± 1711 ( y = 1.1x - 960 )</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left ventricle</td>
<td>Count-based</td>
<td>0.87 ± 1489 ( y = 0.9x - 375 )</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right ventricle</td>
<td>Geometric</td>
<td>0.65 ± 2117 ( y = 0.9x + 579 )</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right ventricle</td>
<td>Count-based</td>
<td>0.79 ± 1671 ( y = 1.1x - 545 )</td>
<td>16</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( p < 0.05 \) for all determinations.

*Statistical analysis done by guest on May 28, 2017*
first-pass technique with geometric assessment of left ventricular volume;\textsuperscript{26, 27} (2) a first-pass technique with a count-based assessment of left ventricular volume;\textsuperscript{28} (3) an equilibrium technique with geometric assessment of left ventricular volume;\textsuperscript{7-10} and (4) an equilibrium method with a count-based assessment of left ventricular volume.\textsuperscript{1-6}

Although the first-pass techniques have shown excellent correlations with cineangiography, they have not been widely applied, as only a limited number of multicrystal scintillation cameras are in use. Equilibrium radionuclide angiography, however, is widely used. Geometric determinations of left ventricular volumes from the equilibrium image have correlated extremely well ($r = 0.84-0.91$) with cineangiographic volumes.\textsuperscript{7-10} Recent reports of count-based volume estimates from the equilibrium image have also correlated well with cineangiographic volumes\textsuperscript{1-6} ($r =$}
left ventricle; \( r = 0.87 \) for the right ventricle. The geometric technique (Simpson’s rule) tended to overestimate the right ventricular volume (fig. 6). Overestimation was less of a problem for the left ventricle (fig. 4).

There are also several methodologic considerations and sources of error inherent in the count-based estimate of ventricular volumes from equilibrium radionuclide studies. Although definition of ventricular borders may still introduce error into the calculations, this is probably less of a problem than with geometric determinations. The count-based method is less dependent on shape assumptions. A related problem, however, is the inability to completely exclude overlapping activity from the atria and great vessels. The importance of this source of error may vary with the patient’s disease; e.g., patients with tricuspid or mitral insufficiency have larger atria and relatively more overlap of activity. The descending aorta may be difficult to identify and exclude from either the cardiac image or background region depending on the viewing angle required for septal separation. Slutsky et al. \(^2\) commented on the problem of intraventricular self-attenuation at larger ventricular volumes. They thought this resulted in smaller slopes and larger y-intercepts for the regression line of left ventricular end-diastolic volumes compared with the regression line for end-systolic volumes. We have not consistently seen this difference, perhaps because of the smaller ventricular volumes in our patients.

Sampling of the patient’s blood can be another source of error if there is a significant interval between the radionuclide collection and the time of blood sampling. Dehmer et al. correct their blood activity for this elapsed time to account for radioactive decay. We did not correct decay, as our samples were all collected within 15 minutes of the radionuclide study, a potential error of less than 3%.

Interest in correcting for attenuation of activity by the chest wall has been limited because of the difficulty of making an accurate correction. Links et al. \(^3\) introduced an attenuation correction in their validation studies. They found a correlation coefficient between radionuclide left ventricular end-diastolic volume and cineangiographic left ventricular end-diastolic volume

### Table 6. Radionuclide-Cineangiographic Volume Correlations: Effects of Red Cell Labeling

<table>
<thead>
<tr>
<th>Blood activity (counts/ml/sec)</th>
<th>Chamber*</th>
<th>( r )</th>
<th>SEE</th>
<th>Linear relationship</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 25</td>
<td>Left ventricle</td>
<td>0.93 ± 26.6</td>
<td>( y = 0.72x + 5.2 )</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right ventricle</td>
<td>0.97 ± 28.5</td>
<td>( y = 1.47x - 18.7 )</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>≥ 25</td>
<td>Left ventricle</td>
<td>0.97 ± 13.2</td>
<td>( y = 1.18x - 21.7 )</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right ventricle</td>
<td>0.85 ± 15.4</td>
<td>( y = 0.93x - 4.2 )</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

\( p < 0.05 \) for all determinations.

*All radionuclide determinations were made using the count-based method with attenuation correction and an assumed chest wall thickness.

Abbreviation: \( n = \) number of patients.

0.96–0.99). Massie et al. \(^5\) compared equilibrium cineangiographic-radionuclide volume correlations for count-based and geometric methods for determining left ventricular volumes and found that the count-based method had a stronger correlation coefficient (\( r = 0.96 \)).

There are several methodologic considerations and potential sources of error in the geometric calculation of right and left ventricular volumes from the equilibrium radionuclide angiogram. The ventricular border may be difficult to define precisely, especially the left ventricular outflow tract and the right ventricular–right atrial border. Geometric calculations also rely on assumptions about ventricular shape. Use of a single image rather than orthogonal views probably magnifies the errors inherent in such assumptions, especially for the crescent-shaped right ventricle. In addition, the diverse ventricular shapes and sizes seen with congenital heart defects may add another source of error. Several authors have attempted to overcome these difficulties by using two views for geometric estimation of radionuclide volumes\(^4\) or by using the first-pass image to help identify valve planes.\(^6\) We limited our geometric assessment of ventricular volume to the single left anterior oblique view. Despite these considerations, and our single view, we found a favorable correlation between cineangiographic end-diastolic volume and radionuclide end-diastolic volumes (\( r = 0.97 \) for the left ventricle; \( r = 0.87 \) for the right ventricle). The geometric technique (Simpson’s rule) tended to overestimate the right ventricular volume (fig. 6). Overestimation was less of a problem for the left ventricle (fig. 4).

### Table 7. Radionuclide-Cineangiographic Volume Correlations: Effects of Patient Size

<table>
<thead>
<tr>
<th>Patient weight</th>
<th>Chamber</th>
<th>Method*</th>
<th>( r )</th>
<th>SEE</th>
<th>Linear relationship</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 27 kg</td>
<td>Left ventricle</td>
<td>Count-based</td>
<td>0.97</td>
<td>± 12.3</td>
<td>1.1x - 10.6</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geometric</td>
<td>0.99</td>
<td>± 12.9</td>
<td>1.2x - 11.9</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Right ventricle</td>
<td>Count-based</td>
<td>0.90</td>
<td>± 7.6</td>
<td>0.83x - 0.52</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geometric</td>
<td>0.94</td>
<td>± 11.5</td>
<td>1.6x - 12.5</td>
<td>8</td>
</tr>
<tr>
<td>≥ 27 kg</td>
<td>Left ventricle</td>
<td>Count-based</td>
<td>0.88</td>
<td>± 33.7</td>
<td>0.74x + 1.02</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geometric</td>
<td>0.97</td>
<td>± 23.5</td>
<td>1.11x - 29.7</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Right ventricle</td>
<td>Count-based</td>
<td>0.92</td>
<td>± 43.4</td>
<td>1.7x - 57</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geometric</td>
<td>0.83</td>
<td>± 62.8</td>
<td>1.7x - 77.5</td>
<td>5</td>
</tr>
</tbody>
</table>

*The count-based method included a correction for attenuation, with an assumed chest wall thickness.

Abbreviation: \( n = \) number of patients.
of 0.96. More important, they found that no regression equation was needed to predict cineangiographic measures. For our attenuation correction, we assumed an attenuation coefficient for the chest wall of 0.1, although the actual attenuation coefficient may vary depending on the amount of scattered photons (Compton effect) counted in the spectrometer window. We also measured the distance from the midportion of the cardiac silhouette to the chest wall rather than attempting to identify the midportion of the ventricular activity. This introduces a potential error due to varying distances of portions of each ventricle from the chest wall.

Changing collimators may affect ventricular volume estimates. We tested this hypothesis in six children and found only a very small difference between medium- and high-resolution collimators. This small difference may be accounted for entirely by intraobserver variability.

Despite reservations about the count-based determination of ventricular volume, we found excellent radionuclide-cineangiographic correlations. As expected, the correlation coefficient was significantly higher for the left ventricle at end-diastole when we corrected for attenuation \( r = 0.94 \) than when we did not \( r = 0.86 \). For the right ventricle at end-diastole, attenuation correction made little difference in the correlation coefficient \( r = 0.93 \) with correction; \( r = 0.94 \) without. The chest wall thickness could be estimated from the body surface area without deterioration in the resulting correlation coefficients. Even with attenuation correction, however, the count-based method slightly overestimated right ventricular end-diastolic volumes and underestimated left ventricular end-diastolic volumes compared with the cineangiographic determinations. We found little change in our radionuclide-cineangiographic correlations in our younger patients or in our patients with less blood activity (tables 6 and 7).

Extrapolation of cardiac output from the radionuclide ventricular volumes provides additional valuable information. For this calculation, the "geometrically" determined cardiac output actually includes a geometric end-diastolic volume multiplied by a count-derived ejection fraction. Despite this mixing of methods, and the potential error introduced by heart rate variability, radionuclide cardiac outputs correlated well with cineangiographic outputs for the left ventricle \( r = 0.87 \). For the right ventricle, the correlation coefficient was much lower for both methods \( r = 0.65 \); count-based, \( r = 0.79 \).

In conclusion, both right and left ventricular volumes can be accurately determined noninvasively in children of all sizes and with diverse cardiac problems by equilibrium radionuclide angiography. Although the count-based method is more versatile in its applicability to both ventricles, the geometric method also provides good correlations, especially for the left ventricle. Attenuation correction significantly improves the correlation coefficient for left ventricular volumes in children. Although correlation coefficients are good, the mean absolute error between radionuclide and cineangiographic volumes is 20–34%. Therefore, radionuclide volumes should be corrected with regression equations, which allow a more accurate determination of absolute ventricular volumes. We offer four regression equations (table 8) for correcting right and left radionuclide ventricular volumes determined by either geometric or count-based methods. These equations are derived from the regression equations in tables 3 and 5.

Table 8. Recommended Regression Equations for Correction of Radionuclide End-diastolic Volumes

<table>
<thead>
<tr>
<th>Ventricle</th>
<th>Method</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left ventricle</td>
<td>Count-based</td>
<td>( V_p = 1.27V_r ) ml</td>
</tr>
<tr>
<td>Left ventricle</td>
<td>Geometric</td>
<td>( V_p = 0.91V_r + 13 ) ml</td>
</tr>
<tr>
<td>Right ventricle</td>
<td>Count-based</td>
<td>( V_p = 0.70V_r + 15 ) ml</td>
</tr>
<tr>
<td>Right ventricle</td>
<td>Geometric</td>
<td>( V_p = 0.77V_r + 7 ) ml</td>
</tr>
</tbody>
</table>

Abbreviations: \( V_p \) = predicted volume; \( V_r \) = radionuclide volume.

References


Radionuclide ventriculography for assessment of absolute right and left ventricular volumes in children.
M D Parrish, T P Graham, Jr, M L Born, J P Jones, R J Boucek, Jr and C L Partain

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