Cardiac Volume in Normal Children and Adolescents

Its Application to Patients with Rheumatic Mitral Insufficiency

By Quang X. Nghiem, M.D., Melvyn H. Schreiber, M.D., and Leonard C. Harris, M.D., M.R.C.P.

SUMMARY
Cardiac volume was determined by a simplified Rohrer-Kahlstorf method in 305 healthy children and adolescents. The ages ranged from birth to 19 years. Height and weight were comparable with normal growth standards. Race, sex, age, height, weight, and body surface area were studied for their value in predicting cardiac volume. Cardiac volume was different in males and females (P < 0.005) and was more closely predicted by weight than by body surface area. In this study body weight has been used as a single predictor of cardiac volume for both sexes. Normal values are presented and the limitations of the technique discussed.

Serial cardiac volume plotted against weight and cardiothoracic ratio plotted against time were correlated with the clinical course in 27 children with pure rheumatic mitral insufficiency. Cardiac volume was found to be superior to the cardiothoracic ratio in reflecting the severity and prognosis of mitral insufficiency. After the cardiac volume had reached a level of 1,100 to 1,300 ml, the course was progressively downhill in 10 adolescents in the absence of evidence of rheumatic activity in most cases.

That the course of rheumatic mitral insufficiency is essentially volume-dependent is a phenomenon of great interest which may be used to assess the severity of mitral regurgitation and its future course.

ADDITIONAL INDEXING WORDS:
Cardiothoracic ratio
Cardiac enlargement

ROENTGENOGRAPHIC projection techniques for determination of the volume of the heart were proposed as early as 1916 by Rohrer and in 1932 by Kahlstorf. Subsequent methods based on their work have been used clinically in Europe. Recently, there has been a renewal of interest in studies of cardiac volume. While normal standards have been determined for adults, there are no satisfactory pediatric data except for infants. Thus, whether the cardiac volume correlates best with body surface area or other parameters of growth in normal children has not been made clear. The usefulness of cardiac volume has even been questioned. Nevertheless, when confronted with a patient with cardiac enlargement, both the clinician and the radiologist require a reasonably accurate and reproducible method of determining heart size.

One purpose of this study is to establish standards for cardiac volume in healthy subjects from birth through adolescence when the growth spurt ceases. Although this is not

From the Departments of Pediatrics and Radiology, University of Texas Medical Branch, Galveston, Texas.

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a longitudinal study, our samples of different age groups are comparable with normal growth data compiled by others.\textsuperscript{16, 17} Relationships have been studied between cardiac volume, on the one hand, and body surface area, weight, height, age, race, and sex on the other. A second aim is to test the superiority of cardiac volume over cardiothoracic ratio as an index of the severity and future course of rheumatic mitral insufficiency. Our experience indicates that not only the ultimate outcome but also the clinical course of rheumatic insufficiency are related to the volume of the heart.\textsuperscript{18}

Methods

Four hundred and fifty-one sets of teleoroentgenograms of the chest in posteroanterior and lateral projections, coded as normal at the University of Texas Medical Branch, were reviewed to ensure that there was no radiographic evidence of cardiovascular or respiratory disease. All the films were exposed with the patient erect except those of small infants in whom anteroposterior supine films were made. The cardiac volume was estimated in each case by a simplified method.\textsuperscript{19} Detailed clinical records of each subject were reviewed. Those with clinical evidence of cardio-pulmonary disease and those who were obese, pregnant, malnourished, or dehydrated, or who had abnormal blood counts or urinalyses were excluded. Subjects whose height or weight was not compatible with growth data of Stuart\textsuperscript{16} or of Falkner\textsuperscript{17} were excluded from the study also.

Three hundred and five subjects were studied. They were attending outpatient clinics or were hospitalized while awaiting elective surgery (for example, repair of hernias and burn scars). Three hundred and five subjects were studied. They were attending outpatient clinics or were hospitalized while awaiting elective surgery (for example, repair of hernias and burn scars). There were 206 Caucasians (including Latin Americans) and 99 Negroes; 158 were males and 147 females. Ages ranged from birth to 18 years and 9 months (fig. 1). Body surface area ranged from 0.18 to 1.87 m\textsuperscript{2}, and body weight from 6.2 to 167 lb. Forty-six subjects with height or weight slightly above or below the fifth percentile were separately analyzed. Since

\begin{figure}
\centering
\includegraphics[width=\textwidth]{age_distribution.png}
\caption{Age Distribution of 305 Normal Subjects Studied}
\end{figure}

The age distribution of the study sample is comparable with the body weight distribution (see figs. 2 and 3).
the prediction of cardiac volume was not affected by extremes of height, relatively small or tall children were included in order to make up a sample representing a healthy population at large. Body surface area was computed from the DuBois and DuBois formula, and all data were statistically analyzed.

In 27 cases of rheumatic mitral insufficiency previously described, the clinical course was correlated with serially determined cardiothoracic ratios and cardiac volumes. During hospitalization for active carditis or cardiac failure, chest roentgenograms were performed monthly or even weekly if cardiac volume was changing rapidly. For outpatients, cardiac volume determinations were usually made at 6 to 12-month intervals. In six of the seven fatal cases, terminal events were documented and in two autopsy was performed. For the total group, the mean duration of follow-up from the initial attack of rheumatic fever was 5 years and 3 months; the median was 4 years and 2 months, and the range was 13 months (patient deceased) to 12 years and 3 months.

Jones’ criteria (revised) were used to define recurrent attacks of rheumatic fever which were presumed to be associated with carditis. Congestive heart failure per se or further enlargement of the heart without pericarditis or involvement of structures previously considered normal (for example, tricuspid valve) were not regarded as indicating a new attack of carditis without other evidence. Left atrial biopsies, mitral valve tissue in two patients, and autopsy material in two others were reviewed by a pathologist who had no knowledge of previously recorded diagnoses. The pathological criteria for rheumatic activity were those of Gross and Ehrlich.

One hundred and ninety-eight determinations of cardiac volume were made and plotted against patients’ weights to determine the trends of cardiac volume changes. In 179 posteroanterior chest roentgenograms, cardiothoracic ratio and cardiac volume per square meter of body surface area (cardiac volume index) were compared as indicators of cardiac enlargement.

The simplified method of estimating cardiac volume was based upon the principle of approximating the heart to an ellipsoid, using a constant magnification factor for the 6-foot distance between target and film (183 cm).

\[
\text{Cardiac volume} = \frac{\pi}{6} \times M \times L \times W \times D
\]

where \(M\) or the correction factor for magnification = \(\frac{1}{1.19}\);

\[
L = \text{long diameter of the heart, from the junction of the superior vena cava with the right atrium, to the cardiac apex.}
\]

\[
W = \text{width of the heart: sum of the distances at right angles to the long diameter of the heart, to the cardiophrenic angle on the right, and to the cardiovascular junction on the left.}
\]

\[
D = \text{depth of the heart from the most posterior aspect of the heart shadow to the posterior border of the sternum.}
\]

Reproducibility of the measurements of cardiac volume was evaluated by comparing the results of the observer reading the total sample (M.H.S.) with those of the other two authors. Delineation of cardiac axes was left to individual discretion. Ninety-three sets of chest roentgenograms selected from all age groups from the total of 305 subjects were independently examined. The value of a predictor of cardiac volume, consistent rater bias, and random error of measurements were studied.

The cardiothoracic ratio was defined as the sum of the maximal distances at right angles from the midthoracic plane (midline of the spine) to the farthest right and left cardiac contours, divided by the maximal internal diameter of the chest at the level of the diaphragm. The transverse diameter of the chest at the level of the right diaphragmatic dome could not be used because the dome itself was included in the cardiac shadow with severe cardiac enlargement.

**Results**

In 261 cases in which body surface area was known, correlation coefficients of various parameters with cardiac volume are given in table 1. No difference was found between cardiac volume in whites and Negroes. Multiple regression analysis showed that age did not contribute to prediction of heart volume.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Correlation coefficient (r)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Race</td>
<td>-0.032</td>
</tr>
<tr>
<td>Sex</td>
<td>-0.036</td>
</tr>
<tr>
<td>Age</td>
<td>0.19</td>
</tr>
<tr>
<td>Height</td>
<td>0.904</td>
</tr>
<tr>
<td>Weight</td>
<td>0.960</td>
</tr>
<tr>
<td>Body surface area</td>
<td>0.954</td>
</tr>
</tbody>
</table>

*Product moment or point biserial as appropriate.
volume when weight was also used as an independent variable. By contrast, consideration of the sex of the subjects improved the prediction of the cardiac volume by weight (table 2). Males and females had different cardiac volumes predicted from weight (t = 6.03, P < 0.005) making the adoption of two regression lines necessary.

Best fit regression equations relating cardiac volume to body surface area on the one hand and to body weight on the other are shown in table 3. The 95% confidence limits

Table 2

Normal Cardiac Volume for Male and Female Subjects as Predicted by Body Weight

<table>
<thead>
<tr>
<th>Body weight (X) in pounds</th>
<th>Cardiac volume (Y) of males (ml)</th>
<th>Cardiac volume (Y) of females (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>95% confidence limits</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>129</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>154</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>204</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>254</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>303</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>352</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>401</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>498</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>547</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>595</td>
</tr>
<tr>
<td></td>
<td>130</td>
<td>644</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>692</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>740</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>788</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>836</td>
</tr>
</tbody>
</table>

For males $Y = 5.620 X^{0.973}$ \(\text{(linear correlation } r = 0.982)\)

For females $Y = 6.628 X^{0.967}$ \(\text{(linear correlation } r = 0.980)\)

Table 3

Comparison of Body Surface Area and Body Weight as Predictors of Cardiac Volume

<table>
<thead>
<tr>
<th>Sample</th>
<th>No. of subjects</th>
<th>Correlation coefficient (r)</th>
<th>Regression equation</th>
<th>Upper limit</th>
<th>Lower limit</th>
<th>% of mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body surface area (Z)</td>
<td>Limited data</td>
<td>261</td>
<td>0.981</td>
<td>Y = 284 Z</td>
<td>413 Z</td>
<td>155 Z</td>
</tr>
<tr>
<td></td>
<td>Males</td>
<td>132</td>
<td>0.980</td>
<td>= 295 Z</td>
<td>434 Z</td>
<td>156 Z</td>
</tr>
<tr>
<td></td>
<td>Females</td>
<td>129</td>
<td>0.987</td>
<td>= 273 Z</td>
<td>388 Z</td>
<td>159 Z</td>
</tr>
<tr>
<td></td>
<td>Limited data</td>
<td>261</td>
<td>0.987</td>
<td>Y = 5.0 Z</td>
<td>6.6 X</td>
<td>3.4 X</td>
</tr>
<tr>
<td></td>
<td>Males</td>
<td>132</td>
<td>0.990</td>
<td>= 5.2 X</td>
<td>6.7 X</td>
<td>3.7 X</td>
</tr>
<tr>
<td></td>
<td>Females</td>
<td>129</td>
<td>0.990</td>
<td>= 4.8 X</td>
<td>6.4 X</td>
<td>3.2 X</td>
</tr>
<tr>
<td></td>
<td>Total data</td>
<td>305</td>
<td>0.985</td>
<td>Y = 4.9 X</td>
<td>6.6 X</td>
<td>3.2 X</td>
</tr>
<tr>
<td></td>
<td>Males</td>
<td>158</td>
<td>0.985</td>
<td>Y = 5.1 X</td>
<td>6.8 X</td>
<td>3.5 X</td>
</tr>
<tr>
<td></td>
<td>Females</td>
<td>147</td>
<td>0.989</td>
<td>Y = 4.7 X</td>
<td>6.3 X</td>
<td>3.1 X</td>
</tr>
</tbody>
</table>

The limited data included 261 subjects whose height and weight were known. \(Y = \text{cardiac volume in milliliters; } X = \text{body weight in pounds; } Z = \text{body surface area in square meters as computed from the DuBois and DuBois formula.}\

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are 32 and 34% above or below the cardiac volume predicted from body weight in males and females, respectively (figs. 2 and 3), as compared with 47 and 42% above or below the predicted value when body surface area is employed. The merits of various formulae correlating cardiac volume with body weight are depicted by correlation coefficients in table 4 (polynomial equations to the second and third power with lower correlation coefficients are not listed). Linear regression equations without intercept have the largest correlation coefficients. Separating males and females, the correlation coefficient improves slightly for females and deviations of the confidence limits are closer to the mean for males.

Evidence of reproducibility of the simplified method of cardiac volume determination is shown in table 5. Using the measurements of observer I (M.H.S.) as a basis for comparison, the mean difference for a single cardiac volume determination by each of the other two observers was 3% (range 0 to 14%), and the maximal difference less than 8% in 95% of the cases. Correlation coefficients in regression of cardiac volume on weight were high in spite of rater bias and random error of measurements.

Cardiac Volume (CV) and Cardi thoracic Ratio (CTR) in Rheumatic Mitral Insufficiency in Children

CTR, as defined, is a relative measurement comparing the horizontal projection of the heart in the frontal plane, with the largest diameter of the chest, used as a correction factor for body size and magnification. The merit of CTR as compared with cardiac volume index is shown here to be independent of growth and stature.

The best fit regression equation of CVI on CTR was a power function. Sex difference in the prediction of CVI from CTR (P < 0.001)
necessitated the adoption of two regression equations (table 6). The corresponding regression lines are shown in figure 4.

In plotting CTR against time for the purpose of correlation with the clinical course, trends of change in heart size were noted in spite of relatively large fluctuations, similar to case 9 in an earlier report. No limits of CTR, however, could be safely proposed as a warning sign of an imminently fatal course. Considering for example a CTR in the range of $0.65 \pm 0.02$, two patients died, five others had a progressively downhill course from this point, and three recovered.

In 27 patients with pure rheumatic mitral insufficiency grouped according to severity, trends of cardiac volume change are depicted in figures 5 through 8.

### Table 4

**Formulae for Prediction of Cardiac Volume by Body Weight**

<table>
<thead>
<tr>
<th>Subjects</th>
<th>No.</th>
<th>Regression equations</th>
<th>Correlation coefficient ($r$)</th>
<th>Upper limit</th>
<th>Lower limit</th>
<th>$%$ of mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>158</td>
<td>$Y = 5.1X$</td>
<td>0.985</td>
<td>6.8X</td>
<td>3.5X</td>
<td>$\pm 32$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Y = 4.6X + 26$</td>
<td>0.956</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Y = 5.62X^{0.973}$</td>
<td>0.983</td>
<td></td>
<td></td>
<td>$+ 36$</td>
</tr>
<tr>
<td>Females</td>
<td>147</td>
<td>$Y = 4.7X$</td>
<td>0.989</td>
<td>6.3X</td>
<td>3.1X</td>
<td>$\pm 34$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Y = 3.9X + 33$</td>
<td>0.965</td>
<td></td>
<td></td>
<td>$+ 36$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Y = 6.67X^{0.906}$</td>
<td>0.981</td>
<td></td>
<td></td>
<td>$- 26$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Y = 78X^{0.618}$</td>
<td>0.895</td>
<td>6.6X</td>
<td>3.2X</td>
<td>$\pm 34$</td>
</tr>
<tr>
<td>Total</td>
<td>305</td>
<td>$Y = 4.9X$</td>
<td>0.985</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: $Y =$ cardiac volume in milliliters; $X =$ body weight in pounds.

### Table 5

**Prediction of Cardiac Volume by Body Weight as Derived from Independent Cardiac Volume Measurements by Three Observers**

<table>
<thead>
<tr>
<th>Observer</th>
<th>No. of cases in samples</th>
<th>Correlation coefficient ($r$)</th>
<th>Regression equations</th>
<th>95% confidence limits</th>
<th>Deviations of confidence limits (as % of mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (M.H.S.)</td>
<td>305</td>
<td>0.985</td>
<td>$Y = 4.93X$</td>
<td>6.62X</td>
<td>3.24X</td>
</tr>
<tr>
<td></td>
<td>261*</td>
<td>0.987</td>
<td>$Y = 4.99X$</td>
<td>6.60X</td>
<td>3.38X</td>
</tr>
<tr>
<td></td>
<td>93</td>
<td>0.988</td>
<td>$Y = 4.84X$</td>
<td>6.59X</td>
<td>3.10X</td>
</tr>
<tr>
<td>II</td>
<td>93</td>
<td>0.988</td>
<td>$Y = 4.86X$</td>
<td>6.54X</td>
<td>3.18X</td>
</tr>
<tr>
<td>III</td>
<td>93</td>
<td>0.988</td>
<td>$Y = 4.91X$</td>
<td>6.61X</td>
<td>3.20X</td>
</tr>
</tbody>
</table>

Abbreviations: $Y =$ cardiac volume in milliliters; $X =$ body weight in pounds.

*The number of cases in which both body weight and surface area were known. The samples were not grouped according to sex.

### Table 6

**Relation of Cardiothoracic Ratio to Cardiac Volume Index in Children and Adolescents with Rheumatic Mitral Insufficiency (Twelve Males and Fifteen Females)**

<table>
<thead>
<tr>
<th>Sex</th>
<th>No. of determinations ($n$)</th>
<th>Regression equation</th>
<th>Correlation coefficient ($r$)</th>
<th>Explained variance ($r^2$)</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>71</td>
<td>CVI = 0.0032 CTR$^{3.053}$</td>
<td>0.920</td>
<td>0.85</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>Females</td>
<td>108</td>
<td>CVI = 0.0564 CTR$^{2.278}$</td>
<td>0.939</td>
<td>0.88</td>
<td>$&lt; 0.001$</td>
</tr>
</tbody>
</table>
CARDIAC VOLUME

Regression lines relating the cardiac volume index (CVI) to cardiothoracic ratio (CTR) for male and female patients with rheumatic mitral insufficiency. \( n \) = number of determinations of CVI and CTR; \( r \) = linear correlation between CVI and power transformation of CTR; and \( r^2 \) = explained variance.

**Group 1 (Asymptomatic with Mild Mitral Insufficiency)**

This group included six males and six females (fig. 5). Characteristic of this group was the normal cardiac volume except for one patient whose heart volume was 6% above the largest value predicted by weight and who had had several attacks of carditis. Cardiac volume during the acute phase of rheumatic fever was normal or nearly normal in six subjects and moderately increased in three others. Only two patients had mild congestive heart failure with the first attack of carditis but the cardiac enlargement never exceeded twice the upper limit of normal volume.

**Group 2 (Moderate Mitral Insufficiency with Signs of Intolerance to Moderate or Marked Exertion)**

This group consisted of two males and three females (fig. 6). In all but one patient the heart was 9 to 70% above the largest predicted cardiac volume by weight. In the presence of acute carditis, heart size exceeded twice the upper limit of normal volume in two patients. Four patients had had congestive failure but after its control the clinical course did not deteriorate. In two subjects, repeated attacks of rheumatic carditis with congestive heart failure responded well to salicylate and steroid therapy.

**Group 3 (Digitalized Cases of Severe Mitral Insufficiency and Symptoms with Mild Exercise or at Rest)**

This group included four males and six females (figs. 7 and 8). Heart volume exceeding two times the upper limit of confidence was noted in all except one. Progressive cardiac enlargement occurred in this patient although there was no evidence of a

**Figure 4**

**Figure 5**

Trends of cardiac volume in male and female children with mild mitral insufficiency (group 1). During the acute attack of rheumatic fever, heart volumes were normal or moderately increased (less than twice the upper limit of normal). Subsequently cardiac volume returned to normal in all but one patient who had several attacks of rheumatic carditis.

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The low incidence of active carditis during terminal episodes of heart failure (two of seven cases) may well be explained by the exclusion of cases in which rheumatic activity was thought to be a major factor in death.18 Myocarditis was not excluded in one patient who died suddenly at home after progressive cardiomegaly for 17 months and atrial fibrillation for at least 22 months. In the remaining six cases, the course ranged from the rapid demise of a female with cardiac volume of 1,580 ml (fig. 8) to intractable congestive failure in another during the last 20 months of her life. Several steroid courses were ineffective in this and two other cases in the terminal months.

**Figure 6**

*Trends of cardiac volume in male and female children with moderate rheumatic mitral insufficiency (group 2). During the acute attack of rheumatic fever, enlargement of the heart up to twice the upper limit of normal volume was observed. In years of follow-up, increase in cardiac volume (9 to 70% over the upper limit of normal) was noted in all except one patient. Second rheumatic attack. Similar but more rapid clinical and hemodynamic deterioration occurred in the two surgically treated patients. Using the usual clinical and laboratory criteria, the downhill course in these two cases was not attributed to active carditis. At surgery no pericardial effusion was noted. Left atrial biopsies showed "late phases"22 in one and were not diagnostic in the other. Unexpectedly low stroke indices (25.4 and 33.4 ml/beat/m²) as compared with normal values,26 1 month postoperatively coincided with cardiac volumes of 86 and 96% above upper limits of normal. Normal stroke indices were observed later when cardiac volumes were almost normal.18*

**Figure 7**

*Trends of cardiac volume in male children with severe rheumatic mitral insufficiency (group 3). Progressive cardiac enlargement contrasts with reduced weight gain. The recovery of the patient whose mitral valve was replaced is striking both in terms of rapid weight gain and diminution in cardiac volume. (Open square indicates inactive rheumatic fever.)*
CARDIAC VOLUME

Figure 8

Trends of cardiac volume in female children with severe rheumatic mitral insufficiency (group 3). Cardiac enlargement contrasting with reduced weight gain in this group is similar to male children of group 3 (fig. 7). During the recovery of one patient whose mitral valve was replaced, reduction in cardiac volume occurred simultaneously with weight gain. (Open circle indicates inactive rheumatic fever.)

With due consideration of possible pericardial effusion, when cardiac volumes reached 1,100 to 1,300 ml, one patient died suddenly and nine others followed a progressively downhill course. Rapid and severe loss of weight (even in spite of edema), together with a steep rise in cardiac volume, was one of the earliest indicators of the terminal decline. Limits of radiologically determined cardiac volume near the time of death were 1,600 to 2,200 ml in six cases. The weights of two hearts were 395 and 520 g, respectively, but radiologically estimated cardiac volumes were 1,550 and 2,200 ml, the second value being augmented by a 200 ml pericardial effusion. Pathological diagnoses were compatible with “middle phases” in the former and “late phases” in the latter.22

Discussion

Limitations of the Radiological Ellipsoidal Technique of Determining Cardiac Volume

Minor variations in radiological technique produce insignificant changes in results,26 especially if the target-to-film distance is long enough, is held constant, and the patient is close to the film.

One possible source of error resides in extending the ellipsoidal approximation to irregular heart contours. In the case of enlarged hearts tending to have two or three equal diameters, the present assumption remains valid. Compared with other techniques, the ellipsoidal method results in a slight underestimation27 but results were within 5% of the displaced cardiac volume for cadavers' hearts.28 A constant magnification factor (M) of \[ \frac{1}{1.19} \] for films exposed at a distance of six feet (183 cm) from the target, was found suitable for a large number of persons. For small infants with an anteroposterior distance of 7 cm and lateral distance of 7 cm from the center of the heart to the film, the basic constant may result in up to 6% underestimation of cardiac volume. Comparing all our data with those of Axén and Lind29 who measured the heart volume in 45 infants by an elaborate technique, we found that the 95% limit of the total group in the present study \((Y = 6.6 X)\) accounted for 41 cases (or 91%). A single constant was therefore used for convenience.

Variations in cardiac volume may occur during change from the recumbent to the erect position,30 from diastole to systole when the heart rate is slower than 70 beats per minute, or during phases of respiration.31, 32

In unfavorable circumstances,26 these factors have been found to amount to less than 12% error at a confidence limit of to.02. Nevertheless, consecutive exposures at right angles, which rarely fall precisely in end systole or end diastole, the relatively fast heart rate in young subjects, and a standardized practice of exposing films in moderate inspiration

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assure reasonable reproducibility of the radiological technique.

Although observer variation resulted in no more than an 8% error in 95% of the cases, a value of 10% is suggested as an index of true change of volume for enlarged hearts because of ease of estimation. Rater consistency falling within 4% of the mean is not different from measurements by separate readers.

A drawback of the method is that estimation of cardiac volume includes the pericardial space and the contents of adjoining vessels. For a given patient, rapid change of adjacent vascular volume is not expected to be large over short periods of observation. Rheumatic pericardial effusion is rarely enormous, nor does it persist in spite of antirheumatic treatment or cause symptoms for months or years as in cases of severe cardiomegaly. When in doubt, serial determinations of cardiac volume, angiocardiography, radioactive scanning, or a diagnostic tap will help in detecting an effusion.

Characteristics of the Study Sample

Selection of normal chest roentgenograms as controls may exclude extremes of normal heart size. However it includes the normal limits as commonly agreed upon by radiologists and cardiologists.

Originally subjects were chosen to cover adequately all age groups (fig. 1). For the first 2 years of life, a larger number were selected to cover the period of rapid growth. A better correlation of cardiac volume with body weight than with age cannot be attributed to choice of sample. Electrocardiograms in 36 subjects (12% of total) were normal. Obese, anemic and pregnant patients were excluded because of likelihood of hemodynamic or blood volume disturbances.

Choice of an Independent Variable in Predicting Cardiac Volume

The use of age as a predictor of cardiac volume in children is based on the supposition that growth is normal. This postulate does not hold in the presence of heart disease. A heart size "normal for age" may be excessively large if the body fails to grow. Other objections include poor correlation of age with heart volume over a longer life span, and aging which introduces factors unrelated to the postulate.

Sex difference in cardiac volume has been a uniform finding in all series comparing males and females except in Lind's study in which an overlap of cardiac volume in both sexes was to be expected in view of the small body weight (292 infants below 12 kg). Normal heart volume in girls as compared with boys appeared neither smaller from 2 to 7 years nor larger after 12 to 13 years. This was in contrast with an earlier report based on differences in cardiothoracic ratio.

The choice of either body weight or body surface area as a predictor of cardiac volume is most difficult. In reported series, neither has superior correlation with heart volume. An apparent paradox is their low correlation in some series. The explanation can usually be found in reviewing these samples. The magnitude of a correlation or regression coefficient depends upon the range of values for the independent variable. Selection of any limited band of body weight or surface area will cause correlation to drop sharply because of restriction in range for the variable. Extrapolation of results from such samples becomes questionable.

A universal finding however is that height does not correlate well with cardiac volume. Its use as an adjunct to weight does not improve the prediction of the latter. In the present study, predicted normal limits of cardiac volume by body weight are closer to the regression lines (29 to 34%) than limits predicted by surface area. The use of weight is more precise and eliminates an additional measurement (height). In heart disease, the ratio of cardiac volume to weight might provide a more sensitive index than the CVI. The advantage of linear regression equations without intercept is evident. The 95% confidence limits were used instead of standard deviation (σ) because the latter should
vary in absolute value with weight itself ($\sigma = \alpha' X$). A clear concept of cardiomegaly is obtained by comparing the excess in volume with the upper limit of normal.

**Cardiothoracic Ratio and Cardiac Volume in Mitral Insufficiency in Children**

Studies of CTR in normal children and adolescents showed that normal values were less than 0.50, and the range of normal variation within 0.10 in the same subjects (for example, range 0.40 to 0.49). In the case of cardiac enlargement secondary to rheumatic mitral insufficiency, CTR was less than twice the upper limit of normal in male or female subjects, whereas CVI was greater than four times the normal upper limit in both sexes (fig. 4). CTR must necessarily be related to CVI in a logarithmic progression. From CTR values of 0.40 to 0.80, the slope of the regression line becomes two times steeper for females. In males, the slope ascends so rapidly that maximum CVI is reached before CTR is in the range of 0.80. The random CTR error of $±0.05$ as in normal subjects corresponds to large variations in cardiac volume when CTR is above 0.60 or 0.70. CTR is thus a poor indicator of cardiac enlargement where accuracy is most needed (fig. 9). Unexplained variance of 12 to 15% is shown by values of $r^2$ in table 6. Weight loss, for example, is accompanied by increased relative cardiac volume but not by a change in the maximal thoracic diameter.

CTR is generally less than 0.50 in normal subjects and variations between 0.40 and 0.50 enable no conclusions to be drawn about differences in cardiac volume between males and females. It is suggested, however, that, beyond a CTR of 0.60, the more reliable technique of cardiac volume determination is preferable (fig. 4).

**Significance of Cardiac Volume in Rheumatic Mitral Insufficiency**

Progressive cardiac enlargement culminating in death in the first two decades is not unique in the present study. Similar observations were made by Noonan and Spencer, but volumetric limits were not stated.

The close correlation between cardiac enlargement and the clinical course of rheumatic mitral insufficiency requires consideration of the underlying mechanism. True cardiac enlargement was confirmed in four group 3 patients in whom the pericardia were opened. The total cardiac weight in two autopsied cases was no more than 25% of the radiographically determined cardiac volume. A significant fact is that with severe cardiac enlargement there are no detectable volume changes during the cardiac cycle. Presumably, the right and left forward stroke volumes diminish relative to increased cardiac volume and fall within the 5% error of the ellipsoidal approximation technique. For this reason, an increase of ventricular residual volume compared with diminution of forward stroke volume is not considered to be responsible for the progressive cardiac enlargement detectable by the technique.

The mitral regurgitant volume during systole subsequently returns from the left atrium to the left ventricle. In either diastole or systole, the left heart volume is augmented by this amount which is accompanied by a proportional increase in the left ventricular residual volume. Atrial residual volume may be large in atrial fibrillation. Progressive enlargement of the left heart occurs if the regurgitant stroke or residual volumes are augmented. Fibrosis and retraction of the mitral valve or chordae tendineae may increase the regurgitation. Further increase of residual volume in the left ventricle or atrium may lead to dilatation of these chambers and perpetuate a vicious cycle. Tricuspid insufficiency may result with right ventricular hypertension secondary to left heart failure or increased pulmonary vascular resistance. Rapid increase in heart volume during the terminal decline may be accentuated by tricuspid regurgitation which was recognized in some cases in this study.

Comparing the three groups of patients (figs. 5 to 8), the results of the present study support the concept that the future course of rheumatic mitral insufficiency is determined by the severity of the initial.
In the presence of cardiac enlargement during the acute phase, recovery was characterized by diminution of cardiac volume. In group 2 patients, significant mitral regurgitation was reflected by increased cardiac volume which remained relatively proportional to growth for many years. The mechanical disadvantage in group 3 patients was such

Figure 9

Cardiac volume determinations in two patients without active carditis. The upper chest roentgenograms are from a patient in group 2, 2 years after the initial attack of rheumatic carditis. The heart was moderately increased in volume and the clinical course was stable. Despite a severe attack of rheumatic carditis with congestive failure in September 1955, this patient was able to play two sets of tennis 11 years later. The lower chest roentgenograms are from a patient in group 3, 16 months after the initial attack of rheumatic carditis. Progressive enlargement of the heart was associated with a rapid clinical decline without detectable acute rheumatic carditis. Replacement of the mitral valve resulted in a rapid reduction of cardiac volume. (See fig. 7.) Similar cardiothoracic ratios in these two patients did not indicate the magnitude of cardiac enlargement or permit prediction of different clinical courses.
that recovery did not occur even in the absence of demonstrable active carditis. Mitral valve replacement in two patients was followed by a gradual return of resting cardiac output to normal levels. Mitral insufficiency per se appears to be at least the major factor in hemodynamic deterioration and its early correction is desirable for individuals in group 3.

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QUANG X. NGHIEM, MELVYN H. SCHREIBER and LEONARD C. HARRIS

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