Angiographic Volume Estimation of Right Ventricle

Re-evaluation of the Previous Methods

Yasuhsa Shimazaki, M.D.; Yasunaru Kavashima, M.D., F.C.C.P.;
Tohru Mori, M.D., F.C.C.P.; Shintaro Beppu, M.D.;*
and Kanji Yokota, M.D.**

Previous angiographic methods for volume estimation of the right ventricle were re-evaluated by ten cast studies as far as the positions of the right ventricular casts were concerned. The spatial orientation of the right ventricular chamber cavity varies clockwise or counterclockwise, in the normal heart. For right ventricular volume estimation, it is important to analyze the right ventricular casts with rotated positions. The casts were studied by biplane cineangiograms with four clockwise rotated positions, which were 0°, 30°, 45°, and 60°. Simpson's rule and the area-length methods were used for angiographic determination of the right ventricular volume. In four positions, four linear regression equations comparing true volumes with calculated volumes had similar values to each other in the two methods. Regression equation comparing true volumes with calculated volumes which contained a total of 40 casts in four positions, yielded a high correlation coefficient ($r = +0.98, p < 0.001$) and small errors in both Simpson's rule and the area-length methods. This study indicates that the right ventricular chamber volume can be accurately estimated with only one regression equation from biplane cineangiograms, even when the right ventricular cavity would have been rotated clockwise or counterclockwise.

In recent years, there has been a distinct tendency to quantitate ventricular performance in clinical hemodynamic investigations. Ventricular volume estimation has been successfully done in left-sided heart evaluations using angiographic techniques in adults as well as in children in the acquired or congenital heart diseases. The same methods as for the left ventricle have been applied to the right ventricular volume estimation, in spite of more complex internal geometry of the right ventricle than the left ventricle. The spatial orientation of the right ventricular cavity in vivo varies not only during the cardiac cycle but also from patient to patient. Therefore, for the right ventricular volume estimation, it is necessary to analyze the right ventricular casts with some degree of rotation around the head-to-foot axis. Previous studies did not take into consideration of variety of the rotation of the right ventricle in vivo. The purpose of this investigation is to analyze the right ventricular casts with some degree of rotation by using biplane cineangiograms. The casts were studied with clockwise rotation, which were 0°, 30°, 45°, and 60° (Fig 1). Simpson's rule

MATERIALS AND METHODS

In Vitro Right Ventricle Casts Studies

Silicone rubber casts were made of right ventricles from the subjects with normal right-sided heart undergoing postmortem examination. Liquid, room-temperature vulcanizing silicone rubber was used to fill the right ventricle prior to fixation by suturing the tricuspid valve and filling the heart through the pulmonary artery. The right ventricles were filled with the silicone rubber at filling pressure of approximately 10 cm H2O while suspended in 90 percent formalin.

The filling pressure was estimated by the height of the liquefied silicone rubber column above the middle of the right ventricle multiplied by the specific gravity (1.18g/ml). After 12 hours, the vulcanized cast was removed from the heart, and the right ventricular portion cut away from the remainder of the cast at the pulmonary valve. The real volume of each cast was determined by water displacement. Silicone rubber casts were themselves radiopaque. 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.

The right ventricular casts were positioned on the table to simulate the normal orientation of this chamber in vivo, i.e., at 0°, and then was rotated in a clockwise manner at positions of 30°, 45°, and 60° (Fig 1). The roentgenograms (silhouettes) in the AP projection at 0°, 30°, 45°, and 60° rotation had corresponding silhouettes in the lateral projection at ±90°, −60°, 45°, and −30° angles, respectively. Therefore,
the casts were analyzed roentgenographically at a wide range of projection from $-90^\circ$ to $+90^\circ$.

For calibration purposes, a metal ball 30 mm in diameter was filmed perpendicular to the AP and Lat x-ray tubes at the same place the cast occupied. The films of the casts were projected onto a drawing board, and the images were outlined by hand. Simpson’s rule and the area-length methods were used to calculate the volume of the cast. In Simpson’s rule, the drawings of the cast were divided into ten slices, and calculated volume was obtained as the sum of the volumes of ten slices.

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

**In Vivo Volume Determination**

Right ventricular volume determinations were performed from biplane cineangiograms. Eight patients were more

![Four different positions of right ventricular casts that are $0^\circ$, $30^\circ$, $45^\circ$ and $60^\circ$ clockwise rotation. The frontal image and its area of the cast at $0^\circ$, $30^\circ$, $45^\circ$, or $60^\circ$ correspond to lateral image and area of same cast at $\pm90^\circ$, $-60^\circ$, $-45^\circ$, or $-30^\circ$ angles, respectively. Lateral image and its area at $0^\circ$, $30^\circ$, $45^\circ$, or $60^\circ$ correspond to frontal image and area of same cast at $\pm90^\circ$, $-60^\circ$, $-45^\circ$, or $-30^\circ$ angles, respectively.](figure1.png)

**Figure 1.** Four different positions of right ventricular casts that are $0^\circ$, $30^\circ$, $45^\circ$ and $60^\circ$ clockwise rotation. The frontal image and its area of the cast at $0^\circ$, $30^\circ$, $45^\circ$, or $60^\circ$ correspond to lateral image and area of same cast at $\pm90^\circ$, $-60^\circ$, $-45^\circ$, or $-30^\circ$ angles, respectively. Lateral image and its area at $0^\circ$, $30^\circ$, $45^\circ$, or $60^\circ$ correspond to frontal image and area of same cast at $\pm90^\circ$, $-60^\circ$, $-45^\circ$, or $-30^\circ$ angles, respectively.

![One of the right ventricular casts. Frontal and lateral images in four positions ($0^\circ$, $30^\circ$, $45^\circ$, and $60^\circ$).](figure2.png)

**Figure 2.** One of the right ventricular casts. Frontal and lateral images in four positions ($0^\circ$, $30^\circ$, $45^\circ$, and $60^\circ$).
than seven years of age and were studied in the postoperative state without shunt or valvular regurgitation. Biplane cineangiocardiograms were filmed at 50 to 70 frames/second after the injection of 1 to 1.5 ml/kg of contrast medium into the right ventricle. The ECG was monitored during the cine, and cycles with ectopic and postectopic beats were not used. Correction was made for x-ray magnification by a metal ball at the end of each study. Left ventricular volumes were determined by the right anterior oblique single plane method. There was no significant difference in heart rate and physiologic state between right and left ventriculographies in the same patient. Left ventricular volumes were calculated using the area-length method with appropriate regression equation determined from left ventricular cast study; \( V_t = 0.89 \times V_c + 9 \); where \( V_t \) means true volume and \( V_c \), calculated volume. Right and left ventricular images were projected onto a drawing board, and end-diastolic and end-systolic frames were drawn.

As a test of the methods, the angiographic stroke volume of the right ventricle was compared with that of the left ventricle in the same subject. This comparison was carried out in eight postoperative patients without shunt or valvular regurgitation.

**RESULTS**

**Right Ventricular Cast Study**

The actual volumes of the right ventricular casts ranged from 11 to 137 ml. One of the ten casts in four positions is presented in Figure 2. The frontal images in the four positions varied only slightly as was also noted in the lateral images. In the area-length method, right ventricular volume calculation was derived by the maximal apex-base distance obtained from the image (silhouette) whose shape is similar to that of the lateral image in the 0° position. All previous studies have utilized the apex-base distance obtained from the lateral image of the right ventricle in this position. Regression analysis comparing true volumes with calculated volumes in each position (0°, 30°, 45°, and 60°) yielded high correlation coefficients \( (r > \pm 0.98) \) in both Simpson's rule (Fig 3) and the area-length methods (Fig 4). Four linear regression equations in four positions had almost the same values in the two methods (Fig 3 and 4). Regression equation comparing true volumes with calculated volumes which contained a total of 40 casts in four positions, also yielded an excellent correlation coefficient both in Simpson's rule \( (r = +0.980, p < 0.001) \) (Fig 5) and in the area-length method \( (r = +0.984, p < 0.001) \) (Fig 6). The correlation coefficients, regression equations, and errors are shown in Figures 5 and 6. There was no significant difference between the errors obtained in Simpson's rule and in the area-length method.

**In Vivo Study**

Clinical application of the methods was tested by

\[
\text{regression equation } r \nonumber \\
\begin{array}{ccc}
0° & V_t = 0.779V_c - 1.807 & 0.989 \\
30° & V_t = 0.790V_c + 0.238 & 0.982 \\
45° & V_t = 0.737V_c + 1.435 & 0.991 \\
60° & V_t = 0.749V_c + 0.836 & 0.995 \\
\end{array}
\]

As a test of the methods, the angiographic stroke volume of the right ventricle was compared with that of the left ventricle in the same subject. This comparison was carried out in eight postoperative patients without shunt or valvular regurgitation.

**RESULTS**

**Right Ventricular Cast Study**

The actual volumes of the right ventricular casts ranged from 11 to 137 ml. One of the ten casts in four positions is presented in Figure 2. The frontal images in the four positions varied only slightly as was also noted in the lateral images. In the area-length method, right ventricular volume calculation was derived by the maximal apex-base distance obtained from the image (silhouette) whose shape is similar to that of the lateral image in the 0° position. All previous studies have utilized the apex-base distance obtained from the lateral image of the right ventricle in this position. Regression analysis comparing true volumes with calculated volumes in each position (0°, 30°, 45°, and 60°) yielded high correlation coefficients \( (r > \pm 0.98) \) in both Simpson's rule (Fig 3) and the area-length methods (Fig 4). Four linear regression equations in four positions had almost the same values in the two methods (Fig 3 and 4). Regression equation comparing true volumes with calculated volumes which contained a total of 40 casts in four positions, also yielded an excellent correlation coefficient both in Simpson's rule \( (r = +0.980, p < 0.001) \) (Fig 5) and in the area-length method \( (r = +0.984, p < 0.001) \) (Fig 6). The correlation coefficients, regression equations, and errors are shown in Figures 5 and 6. There was no significant difference between the errors obtained in Simpson's rule and in the area-length method.

**In Vivo Study**

Clinical application of the methods was tested by

\[
\text{regression equation } r \nonumber \\
\begin{array}{ccc}
0° & V_t = 0.779V_c - 1.807 & 0.989 \\
30° & V_t = 0.790V_c + 0.238 & 0.982 \\
45° & V_t = 0.737V_c + 1.435 & 0.991 \\
60° & V_t = 0.749V_c + 0.836 & 0.995 \\
\end{array}
\]
Simpson's rule

\[ V_t = 0.76V_c + 1.5 \]

\[ r = 0.980 \]

\[ P < 0.001 \]

\[ n = 40 \]

Error (%): 12.39

Area-length method

\[ V_t = 0.76V_c - 0.2 \]

\[ r = 0.984 \]

\[ P < 0.001 \]

\[ n = 40 \]

Error (%): 12.14

Figure 5. Comparison of true right ventricular cast volume with calculated volumes that contained 40 casts in Simpson's rule.

Figure 6. Comparison of true right ventricular cast volumes with calculated volumes that contained a total of 40 casts in the area-length method.
analyzing arrhythmia-free cineangiograms of postoperative hearts without shunt or valvular regurgitation, using separate x-ray correction factors for the right and left ventricle in all subjects. Volume calculations were obtained during end-diastole and end-systole. The area-length method was used to calculate the volumes of the right and left ventricles.

Right ventricular end-diastolic and end-systolic volumes were calculated by using calibration and obtained regression equation of the area-length method and were compared with left ventricular volumes in postoperative patients. A graphic comparison of right and left ventricular stroke volumes for all subjects is shown in Figure 7. Right ventricular stroke volume was almost identical to the left ventricular in the same subject (Fig 7). The dashed line in Figure 7 shows the line with a slope of 45°.

**DISCUSSION**

There have been several reports6-9 concerned with the right ventricular volume estimation by Simpson's rule and the area-length methods which were used as usual methods of the left ventricular volume measurement. Several reports11,12 reported that left ventricular volume determination by these methods correlated well with an irregular or complex geometric configuration of the left ventricular cavity, as occurred with left ventricular aneurysm. Arcilla et al6 reported that the geometric configuration of the chamber is, indeed, not critical in the area-length method for right ventricular volume estimation. The planar areas of the frontal and lateral projections are most important.

Variations in the QRS axis from +30° to -30° of the chest lead tracings of normal subjects may be related to some degree of clockwise or counterclockwise rotation of the heart along its apex-base axis.13 This suggests that the right ventricular chamber cavity rotated clockwise or counterclockwise in normal subjects. For the volume estimation of the right ventricle, it is important to analyze the casts rotated. We have found only one similar report which investigated the influence of spatial orientation and cardiac phase on the regression equation.14 They examined the right ventricular casts in seven positions and showed a similar value of regression equation in seven positions both in Simpson's rule and in the area-length methods. They emphasized that the positional variations of the regression equations are pronounced for the right ventricle. But, bi-directional angiograms which we can see are only silhouettes of the right ventricular chamber. The precise direction of the right ventricle cannot be exactly determined from biplane cineangiogram. Therefore, it is not practical in clinical study to make a correction factor (regression equation) in each patient, or in each systolic or diastolic phase for the right ventricular volume estimation as they reported.

In our investigation, the right ventricular casts were studied with four different positions in which the right ventricle would have been placed in vivo. Regression equation comparing true volumes with calculated volumes which included a total of 40 casts, yielded an excellent correlation coefficient (r > +0.98 p < 0.001) and small values of error in both methods. Our results demonstrate that it is not necessary to make each regression equation in each patient.

It is well known that stroke volumes calculated with left ventriculograms were coincident with those measured by the thermodilution method or indicator dilution method by using indocyanine green.15 They are, however, fundamentally different methods. Angiographically, right ventricular stroke volumes were identical to left ventricular stroke volumes in the previous studies.6-9 In this study, right ventricular stroke volumes were identical to left ventricular stroke volumes measured by angiograms. The right ventricular volume calculations by the area-length method and by Simpson's rule method were identical. The regression equation of the area-length method was applied to calculate the left ventricular volume in our clinic. Therefore, the area-length method was used for an angiographic comparison of right and left ventricular stroke volumes in this study.

These results indicate that the right ventricular chamber volume can be accurately estimated with only one regression equation from biplane cineangiograms, even when the right ventricular cavity would have been rotated clockwise or counterclockwise.