A new scintigraphic method for determining left ventricular volumes

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ABSTRACT A new scintigraphic count-based method for measuring absolute left ventricular volumes is presented. It is a fast and simple technique that allows geometrical assumptions to be avoided and is free of radiation attenuation corrections. This method requires the acquisition of an image of the left ventricle in the right anterior oblique projection and the collection of gated blood pool images in the left anterior oblique projection. To assess the accuracy of the method scintigraphic stroke volumes were compared with those derived from thermodilution measurements during cardiac catheterization in 20 subjects, and to assess its precision the technique was applied to phantom data of known radionuclide volumes. Excellent correlations were found between the scintigraphic and both the thermodilution ($r = .98$) and phantom data ($r = .99$). The reproducibility ($r = .97$) of results was investigated by repeating data acquisition and analysis for 15 subjects on two different days, and the interobserver variability ($r = .97$) of the method was studied by having two computer operators calculate volumes for the same patient data for 20 randomly selected studies.

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SEVERAL METHODS have been reported for estimating left ventricular volumes with the use of scintigraphic data and all of these come under the general categories of geometric or count-based methods. Geometric methods such as the Dodge-Sandler approximation\(^1\) are convenient in that they do not require any information in addition to gated equilibrium data in one view, but have the disadvantage of not taking into account the variety of shapes of the ventricular chamber.\(^2\) Also, these geometric techniques are not particularly well suited to the analysis of scintigraphic data since the resolution of the boundaries of the ventricular walls is poorer than for contrast angiocardiographic images.\(^3\)

Count-based methods require the accurate drawing of ventricular edges too, but are not as sensitive to outlining errors as geometric methods.\(^4\) In general they are free of assumptions about the actual shape of the ventricle being imaged.\(^5\) However, some of these techniques rely on assumptions about the average attenuation of gamma rays being emitted from the heart chambers.\(^5\) while others require removal, processing, and counting of blood samples after the gated equilibrium studies.\(^6\) Means of correcting for attenuation by placing a source within the patient’s esophagus have been implemented,\(^7\) but may not gain wide acceptance because of the inconvenience to the patient. Aside from the additional time and effort on the part of technologists that these methods require, they can yield inaccurate results in children and in obese patients, as evidenced by the wide range of average attenuation coefficients obtained by these methods.\(^8\)

The new method described below does not make assumptions concerning average ventricular shapes and avoids the problem of radiation attenuation corrections. Its implementation only requires that an image of the left ventricle be obtained in the right anterior oblique projection separate from the acquisition of gated equilibrium blood pool data in the left anterior oblique projection. This new technique requires little additional time or expertise on the part of personnel, beyond that necessary for the scintigraphic determination of the ejection fraction, in order to measure the left ventricular volume.

To assess the precision and accuracy of the values for ventricular volumes obtained by this new technique, stroke volume calculations were compared with those obtained from thermodilution cardiac catheter-
The advantage of this type of comparison is that thermodilution values are free of geometric assumptions and have been shown to yield accurate and precise measurements of cardiac output and stroke volume. Furthermore, thermodilution measurements have been shown to be insensitive to the volume and temperature of injectate under controlled conditions, whereas injection of contrast dye has been observed to alter the function of the left ventricle itself.

**Methods**

**Rationale for use of the scintigraphic technique.** This new scintigraphic method is based on the observation that the pixel of the left ventricle that has the most counts at diastole as seen in the left anterior oblique view should correspond to the deepest region of the left ventricle (figure 1). This region appears as the widest part of the ventricle when viewed in the right anterior oblique projection 90 degrees away from the left anterior oblique projection. The only likely circumstance in which this assumption may be invalid is in the case of a large aneurysm that is off center from the left or right anterior oblique axis. This case could be handled by choosing a section of the ventricle that excludes the aneurysm regardless of whether that section passes through the deepest ventricular region, although this modification was not necessary for any of the patients or volunteers involved in this study.

Visualizing an isolated left ventricle for the right anterior oblique equilibrium view is rarely possible, but during the first pass of a bolus of radionuclide tracer the left and right ventricles are easily separated (figure 2). It was from the right anterior oblique first-pass data that a measurement of the depth (L, in units of pixels) was obtained that corresponded to the pixel of highest count rate of the ventricle at diastole in the left anterior oblique view (figure 3). Dynamic images that showed the left ventricle most clearly were summed and the resulting image was enhanced to best display the left ventricle.

Since this is a composite image of several heartbeats, the ventricle is blurred by motion, and the widest dimension of the image is the depth at end-diastole. Other data collection techniques for measuring depth are plausible, such as the gated first-pass method or, for the patient whose left ventricle is much larger than his right ventricle, gated equilibrium left posterior oblique acquisition. However, since the dynamic study is the simplest to implement and the least prone to accidental loss of right anterior oblique data, it was the method chosen for this study.

If it were known beforehand what left anterior oblique angle would optimize separation of the ventricles for the gated equilibrium study for a given patient, a right anterior oblique angle could be chosen that would be exactly 90 degrees away. Since this is not ordinarily the case, an average right anterior oblique angle of 50 degrees was used based on an average left anterior oblique angle of 40 degrees. The implications of this restriction are examined further in the Discussion section below, and in Appendix 1. Caudal tilt was used in 11 of the 20 patients in whom thermodilution data were obtained, with a mean value of 2 ± 2 degrees (range 0 to 5). This small average tilt angle would have negligible influence on the measurement of ventricular depth and, as is discussed in Appendix 1, would contribute at most a 5% error for the maximum tilt angle of 5 degrees.

To convert the depth of the ventricle as measured in pixels to units of length, the x and y position signals of the gamma camera were precalibrated to span 18 cm in 64 pixels so that the magnification factor (m) = 0.281 cm/pixel. The ventricular depth (in cm) is then mL, where L is the measurement of depth from the right anterior oblique first-pass data, and the cross-sectional area of one pixel (in cm²) is m². This means that the deepest column of blood corresponding to the maximum diastolic count per pixel (M), as seen in the left anterior oblique view, must have a volume of Lm³ (figure 1). Assuming the tracer is uniformly distributed, the observed count density (C) of the blood is

\[ C = \frac{M}{Lm^3} \]  

Therefore, the volume (Vd) of the ventricle at end diastole is

\[ V_d = \frac{D}{C} = D\frac{Lm^3}{M} \]  

where \( D \) is the observed total count rate from the ventricle at end-diastole. All count rates are background-corrected values. Likewise, the volume of the blood in the ventricle at end-systole (Vs) is

\[ V_s = S\frac{Lm^3}{M} \]  

where \( S \) is the observed count rate at end-systole. The stroke volume (SV) is

\[ SV = (D - S)\frac{Lm^3}{M} \]

In the computation of diastolic volume with equation 2 the ratio of observed count rates \( D \) and \( M \) is used. The overall attenuation of radiation by structures between the blood of the left ventricle and the detector should be virtually the same for the deepest column of blood (corresponding to \( M \)) and for the sum of all columns of ventricular blood (corresponding to \( D \)). Thus, this method for determining volumes is independent of attenuation, as is further examined in Appendix 2. In this sense it is comparable to a previously proposed volume method in which counts in the aorta and those in the left ventricle are compared. However, it is frequently difficult to visualize the aorta clearly enough with the gated blood pool method to make use of this method.

**Method for collection of scintigraphic data.** Each study patient was first injected with 2 ml of stannous pyrophosphate and after 30 min was positioned supine under a gamma camera (Picker 4/15) interfaced to a computer (DEC PDP 11/34). A

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**FIGURE 1.** The slice through the left ventricle that contains the highest count rate as viewed from the left anterior oblique (LAO) projection. The pixel that contains the most counts corresponds to the deepest region of the slice, the dimension of which is measured by viewing the slice from the right anterior oblique (RAO) projection 90 degrees away from the left anterior oblique projection. Each voxel has a volume \( m^3 \), so that the deepest region of the slice is a column of \( L \) voxels having a total volume of \( Lm^3 \).
FIGURE 2. The passage of radioactive tracer through the heart recorded by 128 × 128 matrixes of a 36 cm × 36 cm field of view. The left ventricle is seen most clearly in frames 6 through 8.

parallel-hole high-resolution collimator was used, with the detector positioned at a right anterior oblique angle of 50 degrees over the chest region. It was sufficient to deliver the injection of 20 mCi of \(^{99m}\)Tc-labeled sodium pertechnetate into the left antecubital vein with a 20-gauge needle by merely injecting rapidly, since all that was needed from the first-pass right anterior oblique data was a clear image of the left ventricle. The computer collected the data as matrixes of 128 × 128 pixels covering a 36 cm × 36 cm field of view at 1 frame/sec for 90 sec. The use of this wide field of view eliminated the possibility of missing the heart chambers during the first pass of the bolus of radioactive tracer.

Five minutes were allowed to elapse to ensure that the tracer became thoroughly mixed with the blood. Each patient was then

FIGURE 3. The composite contrast-enhanced right anterior oblique view of the left ventricle (left) and the end-diastolic frame of the left anterior oblique view of the heart (right) from the same patient. The right anterior oblique image is the sum of frames 6 through 8 of figure 2, one quadrant of which has been expanded to a 64 × 64 matrix covering an 18 cm × 18 cm field of view, the same magnification as the accompanying left anterior oblique image. The manually drawn outline of the left ventricle is displayed in both images, along with the horizontal bar depicting the widest extent of the left ventricle as seen from the right anterior oblique view.
repositioned with the detector placed at whatever angle optimized visualization of the septum, which in this study averaged 40 ± 7 degrees (range 33 to 55 degrees) in the left anterior oblique projection. Gated data were acquired for 24 frames per heart cycle for a total of 5 million counts with a magnification of 64 pixels spanning 18 cm. All data were stored on magnetic disk for subsequent processing. In some medical conditions, such as atrial fibrillation, the heartbeat was so irregular that acquisition of the usual gated synchronous images was precluded. When this was the case (four patients), data were collected in "gated list mode" on 28 megabyte disks for as long as 25 min and later formatted as a gated dynamic study for a representative range of heartbeats.

Method for processing of scintigraphic data. The left anterior oblique gated equilibrium data were first processed with the use of algorithms developed at Vanderbilt University. Each frame was time-averaged with its neighbors and space-smoothed with a 9-point smoothing operator having a kernel of 6:2:1. A human observer viewed the computed ventricular data and then manually drew an estimate of the ventricular outlines for both end-diastolic and end-systolic frames. This observer also drew a background-correction region on the systolic frames between the three and five o’clock positions, two pixels beyond the end-systolic ventricular outline (figure 4). These images and outlines were stored for use in subsequent computations.

Sequential frames of right anterior oblique first-pass images were next examined to locate the left ventricle and frames were summed to yield an image of the isolated left ventricle during that part of the dynamic study after passage of the bolus through the right ventricle and before the appearance of the bolus in the aorta. The quadrant of the 128 × 128 matrix that contained the ventricle was then isolated and redisplayed as a 64 × 64 matrix, so that right anterior oblique and left anterior oblique images of the heart were of the same magnification (figure 3). A 9-point smoothing operator was applied to a contrast-enhanced display of the image in order to obtain what appeared to be the most distinct image of the left ventricle. By direct visual comparison of the left anterior oblique and right anterior oblique views of

The manually drawn outlines of the ventricles and background-correction region are superimposed on the images.

FIGURE 4. End-diastolic (right) and end-systolic (left) scintigraphic images of the left anterior oblique projection of the heart. The manually drawn outlines of the ventricles and background-correction region are superimposed on the images.
TABLE 1
Clinical data

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AF = atrial fibrillation; CAD = coronary artery disease; 3VD = three-vessel disease; 2VD = two vessel disease; MS = mitral stenosis; AS = aortic stenosis; TI = tricuspid insufficiency; AI = mitral insufficiency; AI = aortic insufficiency.

Included in this study who experienced any cardiac event or received therapy thought likely to alter the function of the left ventricle between the two studies. Also, patients were excluded if their severity of stenosis or insufficiency was assigned a value of 2+ or greater (on a scale of 0 to 4+) by the cardiologists observing the passage of the contrast dye during the angiographic examination, since for the stroke volumes derived from thermodilution data represent only the forward component of the total stroke volume, whereas the scintigraphic method measures total ventricular stroke volume.

A separate group of nine patients and six normal volunteers were studied on two separate occasions (not sooner than 1 day apart and not later than 1 week), during which right anterior oblique first-pass and left anterior oblique gated equilibrium scintigraphic data were collected. All of these subjects signed consent forms. The second study was set up by a technologist who had no knowledge of the left anterior oblique angles and caudal tilts used for the first study.

Phantom studies. To evaluate the ability of the method to measure known volumes, Florence flasks of capacity ranging from 50 to 500 ml were filled with $^{99m}$Tc in water at a concentration of 5 $\mu$Ci/ml to simulate conditions in a typical patient. The flasks were placed in a water phantom having a concentration of 0.5 $\mu$Ci/ml to simulate typical background count rates, and known volumes from 20 to 500 ml were consecutively placed in the flasks. Human electrocardiographic R wave triggers were used to permit the accumulation of simulated gated equilibrium data that were analyzed as if they were patient data collected in a left anterior oblique projection. One frame of data at each volume level was used as if it were a right anterior oblique frame and the left and right anterior oblique frames were entered into the computer program as if they were patient data.

It was also possible to determine maximum lateral dimension of liquids in the flasks by measuring the widest extent of the Florence flasks and then subtracting the thickness of the glass walls. The resultant dimension corresponded to the depth of the human heart seen from the right anterior oblique projection.

Results

The results of analyzing the phantom data as if they were patient data are graphed in figure 5 vs the true volumes of radioactive fluids placed in the flasks. The SEE was 15 ml and the average absolute error (AAE), 6 ± 5%. As for the comparison of the depth measurement to the actual maximum diameter of radioactive fluid, the correlation was $r = .99$ (with a slope of the least squares fit line of 0.99 ± 0.03 and a y intercept of 0.4 ± 0.3 cm), with an SEE of 0.26 cm (corresponding to 0.9 pixels) and an AAE of 3 ± 3%.

Figure 6 demonstrates the correlation between stroke volumes determined from thermodilution data and those measured by the new scintigraphic technique in the 20 patients. The correlation was $r = .97$, with a slope of the fitted curve of 0.89 ± 0.04 and a y intercept of 7 ± 3 ml. The SEE was 4 ml and the AAE 5 ± 4%.

The reproducibility of results of the scintigraphic studies were assessed by analyzing the two sets of left anterior oblique gated equilibrium and right anterior oblique first-pass data that were acquired on two separate occasions in 15 human subjects. The two groups of data were analyzed by the same computer technologist independently on two separate occasions. The correlation was $r = .98$ (slope = 1.02 ± 0.04; intercept = 1 ± 4 ml), with an SEE of 12 ml and an AAE of 11 ± 3%.
FIGURE 6. Relationship between stroke volumes measured by the scintigraphic method and thermodilution measurements.

10%. In a separate regression analysis of the end-systolic volume computations for the two data sets the correlation was \( r = 0.98 \) (slope = 1.05 ± 0.06; intercept = -1 ± 5 ml), with an SEE of 11 ml and an AAE of 12 ± 9%. The two different end-diastolic volume computations showed a correlation of \( r = 0.96 \) (slope = 0.97 ± 0.08; intercept = 8 ± 11 ml), with an SEE of 14 ml and an AAE of 9 ± 5%. Ejection fractions for the separate analyses correlated with an \( r = 0.98 \) (slope = 1.02 ± 0.05; intercept = 0 ± 3%), an SEE of 4%, and an AAE of 6 ± 7%. Depth measurements from the right anterior oblique view for the two data groups also correlated (\( r = 0.89 \); slope = 1.15 ± 0.16; intercept = -4 ± pixels), with an SEE of 2 pixels and an AAE of 6 ± 5%.

In a test of the interobserver variability, 20 patient studies were chosen at random and analyzed independently by two people. The overall correlation between their ventricular volume calculations was \( r = 0.97 \) (slope = 1.00 ± 0.05; intercept = 7 ± 5 ml), with an SEE of 16 ml and an AAE of 17 ± 14%. The correlation between the two determinations of end-systolic volume was \( r = 0.97 \) (slope = 1.00 ± 0.06; intercept = 7 ± 4 ml), with an SEE of 13 ml and an AAE of 19 ± 15%. The correlation between the end-diastolic volume computations was \( r = 0.93 \) (slope = 0.99 ± 0.09; intercept = 9 ± 12 ml), with an SEE of 19 ml and an AAE of 15 ± 12%. Values for ejection fraction correlated with an \( r = 0.97 \) (slope = 1.02 ± 0.06; intercept = 1 ± 4%), an SEE of 5%, and an AAE of 9 ± 5%, and those for right anterior oblique depth correlated as \( r = 0.78 \) (slope = 0.86 ± 0.16; intercept = 2 ± 4 pixels), with an SEE of 2 pixels and an AAE of 8 ± 6%.

Discussion

Errors in the quantities \( m, D, L, \) and \( M \) all contribute to the overall error in computed volumes. In this study the calibration factor \( m \) was determined with \( \frac{1}{4} \) inch bar phantoms and consequently the error in this quantity was 3 mm in 18 cm for a 2% uncertainty. In the 20 patients in whom thermodilution data were obtained the average end-diastolic background-corrected count rate was \( 7612 ± 4107 \) counts (range 2079 to 13,463), with an average background of \( 16 ± 7 \) counts/pixel, so that errors associated with diastolic count rates were only 1% to 2%. The error in measuring the ventricular depth was denoted as \( \Delta L, \) and as presented in the Results section above, the SEE for both the reproducibility study and the interobserver variability study was 2 pixels, while for the phantom study it was 1 pixel. Thus, \( \Delta L \) is 1 or 2 pixels out of an average of \( 25 ± 4 \) pixels, corresponding to ventricular depths of \( 7.0 ± 1.1 \) cm (range 5.6 to 9.6). The error in the maximum count rate is taken to be the standard deviation, \( \sigma, \) of all 8 pixels that surround the pixel of the highest count rate. In general, the larger the ventricle and the more data that are acquired, the smaller the computed error will be. The expression for the computational error, \( \Delta V_d, \) of the diastolic volume is

\[
\Delta V_d = V_d \left[ (\Delta L/L)^2 + (\sigma/M)^2 + 1/D \right]^{1/2}
\]

Similarly, the computational error, \( \Delta S_V, \) in the stroke volume is

\[
\Delta S_V = S_V \left[ (\Delta L/L)^2 + (\sigma/M)^2 + 1/D + 1/S \right]^{1/2}
\]

The largest contribution to the computed error comes from the measurement of the ventricular depth. Figure 7 graphs the average percent computational error when equation 5 is used for hypothetical spherical ventricles, assuming an average count density of 5 \( \mu Ci/ml \) and errors in the depth measurement of 1 and 2 pixels. From this graph it can be seen that computed errors on the order of 10% would be expected for the average range of human end-diastolic volumes of 88 to 158 ml (70 ± 20 ml/m²).25

As indicated above, several sources of error may detract from the precision with which volumes may be measured by this method, the greatest of which is the determination of the ventricular depth. The computer technologist must isolate that part of the right anterior oblique first-pass study during which activity has cleared the lungs and before it has begun to recirculate appreciably. He must then discriminate between the
ventricular boundary and possible interfering background structures, particularly residual activity in the right ventricle. Contrast enhancement, smoothing, interpolating, and slice profiles are all tools available to aid in the definition of the left ventricle, but ultimately it is a human decision as to what is and is not the left ventricle and consequently as to what the depth of the ventricle is. But this is also true of the definition of the ventricular edges as seen in the left anterior oblique view, and consequently as to what the diastolic and systolic counts are. The measurement of the ventricular depth involves the same kind of judgments as are made in the assessment of ventricular edges, and these are made routinely for the calculation of ejection fractions and their validity is generally accepted. Thus, if reliable ejection fractions can be obtained by the standard procedures of nuclear medicine, it should also be possible to make accurate measurements of ventricular volumes with the equations given above, as the results illustrated in figures 5 and 6 demonstrate.

It should be noted that an advantage of this new method is that it relies on only one direct dimensional measurement, unlike the various geometric methods. In the method described here it is the counts within the outlines that are used as input for volume calculations, not the dimensions of the outlines. Relatively small errors in D and S result from small alterations of the outlines since the regions in which outlines are drawn border background areas. The incorrect inclusion of a few counts as a result of too generous an outline will to some extent be corrected by the subtraction of the background counts. This is in contrast to the case in geometric methods such as the Dodge-Sandler model, in which small changes in the outline often produce large changes in computed volume.

In choosing a right anterior oblique angle of 50 degrees while using that left anterior oblique angle that best separates the right and left ventricles, there is the danger of incorrectly estimating the ventricular depth because the data is not being collected in perpendicular views. Often the ventricle is observed to be as wide as it is deep, but occasionally it is seen to be quite elongated. This is not a serious problem, since even in the extreme case of a ventricle that is twice as deep as it is wide, an error of 10 degrees in the right anterior oblique positioning would result in an error of less than 4.2% in measuring the depth. Even for the largest of ventricles (10 cm depth) this would underestimate L by no more than 1 pixel, and therefore add an error in calculated volumes of only a few percentage points (Appendix 1).

An even less troubling potential source of error is the assumption that the maximum count rate M and the total diastolic count rate D result from radiation experiencing the same average attenuation as it is emitted from the left ventricle. Attenuation of radiation by the blood itself inside the ventricle is significant, but on the average both M and D will have been attenuated by the same amount. Hypothetical calculation with data from a spherical ventricle having a volume of 500 ml shows that the attenuation coefficients of M and D differ by only 2%, as shown in figure 8. Thus, added errors due to self-attenuation by ventricular blood will

FIGURE 7. The average percent computational error in ventricular volume assuming a spherical ventricle with a 5 μCi/ml tracer concentration. Curves are shown for errors in the right anterior oblique depth estimation of 1 and 2 pixels.

FIGURE 8. The percent error as a result of self-attenuation of radiation by the blood itself within a hypothetical spherical ventricle.
be on the order of only 1% in the most extreme case (Appendix 2).

Another source of error that was investigated was the possibility of changes of the magnification factor m with changes in distance from the collimator. A bar phantom and flood source were used to collect static images of the phantom when it was 0 to 22 cm away from the parallel-hole high-resolution collimator. The resolution is indeed degraded as the distance from the collimator increases, but the magnification factor does not change.26

In conclusion, this new method of measuring ventricular volumes is independent of ventricular shapes and is virtually free of errors as a result of radiation attenuation. It yields accurate stroke volume values, as demonstrated by the close correlation to thermodilution stroke volume values, and is precise to 8% to 12%. Because it is easy to perform and efficient with respect to use of personnel time, it can be applied routinely to all patients in whom a radionuclide wall motion study is indicated, even those patients experiencing arrhythmias during the study.

We thank David Brock, Electra Markopoulos, and Richard Nickel for technical assistance, and Marge Zamanski for secretarial assistance.

References

Appendix 1
Consider the case of a ventricle that is elliptical through its deepest slice, has a major axis (a) along the left anterior oblique line of sight, and a minor axis (b) (figure 9). The right anterior oblique projection should be perpendicular to the left anterior oblique projection, but it is conceivable that the right anterior oblique projection used to collect the first-pass data could be off by angle θ from the direction perpendicular to the left anterior oblique projection used to collect the gated equilibrium data. Then the width would be measured incorrectly as mL = 2r, which is different from the correct value of 2a.

From the polar equation for an ellipse
\[ r^2 = \frac{a b^2}{a \sin^2 \theta + b \cos^2 \theta} \]  
(7)
the ratio of r to a is
\[ r = \frac{a \varepsilon}{(\sin^2 \theta + \varepsilon^2 \cos^2 \theta)^{1/2}} \]  
(8)
for eccentricity \( \varepsilon = b/a \). In the extreme circumstance that \( \theta = 10 \) degrees and \( \varepsilon = 2 \), the ratio r/a differs from 2.0 by only
4.2%. And for the same angle of \( \theta = 10 \) degrees but for \( \epsilon = \frac{1}{2} \), the ratio \( r/a \) differs from \( \frac{1}{2} \) by only 0.5%. Thus, for the extreme case of the ventricle being twice as deep as it is wide, a positioning error of as much as 10 degrees contributes to errors in the depth measurement of less than 4.2%.

The same figure is appropriate for an analysis of the contribution of the caudal tilt to errors in measuring the ventricular depth. If we again assume that the cross section of the ventricle seen from the right anterior oblique projection is an ellipse of eccentricity \( \epsilon = 2 \), then equation 8 implies that the error in the measurement of \( r \) is less than 5% for an angulation error of 5 degrees.

**Appendix 2**

Assume that the ventricle is a sphere of radius \( R \), the center of which is at a depth \( Z_o \) beneath a planar chest wall (figure 10). If \( \mu \) is the attenuation coefficient for tissue and is assumed to cause the same attenuation as blood, then the total amount of counts \( D \) observed by a detector equipped with a parallel-hole collimator parallel to the chest is

\[
D = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{-\mu z_o} e^{-\mu r} dz dr
\]

\[
= \frac{4\pi R^3 e^{-\mu z_o}}{(\mu R)^3} \left[ (\mu R) \sin h (\mu R) - \cos h (\mu R) \right] \quad (9)
\]

where \( \rho \) is the average equilibrium count density in units of Bq per milliliters of blood. The maximum count rate \( M \) seen by the detector through a square window of cross-sectional area \( m^2 \) centered on the deepest part of the ventricle (figure 10) is

\[
M = \frac{4\pi R^3 e^{-\mu z_o}}{(\mu R)^3} \left[ (\mu R) \sin h (\mu R) - \cos h (\mu R) \right] \quad (10)
\]

where \( L \) is the number of pixels of volume \( m^3 \) at the deepest extent of the ventricle (\( R = Lm/2 \)).

Thus, the diastolic volume \( V_d \) as computed from equation 2 above is

\[
V_d = DLm^3/M = \frac{4\pi}{3} R^3 \left[ \frac{(\mu R) \cos h (\mu R) - \sin h (\mu R)}{(\mu R)^2} \right] \quad (11)
\]

In the limit of no attenuation this reduces to

\[
V_d \lim_{\mu R \to 0} = \frac{4\pi}{3} R^3 \quad (12)
\]

as one would expect. The percent error in the computed volume vs the actual volume of a hypothetical spherical ventricle is graphed in figure 8. From this plot it can be seen that even for the largest of ventricles, computation of the diastolic volume with equation 2 would be incorrect by only 2% due to the self-attenuation of radiation by the blood in the ventricle.
A new scintigraphic method for determining left ventricular volumes.
K Nichols, M H Adatepe, G H Isaacs, O M Powell, D E Pittman, T C Gay and F R Begg

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