Direct Determination of the Attenuation Coefficient for Radionuclide Volume Measurements

Andrew M. Keller, Theodore R. Simon, Thomas C. Smitherman, Craig R. Malloy, and Gregory J. Dehmer

Medical Service (Cardiovascular Section) and the Nuclear Medicine Service at the Dallas Veterans Administration Medical Center; and the Departments of Internal Medicine (Cardiology Division) and Radiology, University of Texas Health Science Center at Dallas

Correcting for the attenuation of photons between the cardiac chambers and chest surface is crucial for accurate nongeometric ventricular volume determinations from equilibrium radionuclide angiograms. Previous techniques have assumed that the attenuation coefficient of water for ^{99m}Tc (0.15/cm) should be used for this correction. In this study, this assumption was tested directly by measuring attenuation of the activity of a radioactive source within the right and left cardiac chambers. The balloon of a flow-directed catheter, filled with ^{99m}Tc, was used as a source and its depth within the body was measured with biplane fluoroscopy. In ten patients, a total of 36 measurements of attenuation were made. With linear regression analysis, the overall calculated attenuation coefficient, μ, was 0.12/cm (standard error of slope = 0.01, R = 0.93). Although the mean value of μ varied from 0.08 to 0.13 for four different intracardiac locations these differences were not significant. These direct measurements indicate that the attenuation of photons in the heart is not equivalent to that of water and suggest that an attenuation coefficient of 0.12/cm should be used in analyzing ventricular activity.

J Nucl Med 28:102–107, 1987

Previous studies with equilibrium radionuclide ventriculography have demonstrated that left ventricular volumes can be estimated by count-based techniques (*1–4*). Initially, scintigraphically-determined volumes either were not corrected for attenuation (*1*) or were corrected by employing a linear regression relationship developed from angiographic volumes (*2–4*). These methods provided acceptable results in many patients. However, because attenuation varies among individuals, the correlation with actual volumes diminished at the extremes of body size. Subsequently, investigators have attempted to correct for tissue attenuation by estimating the depth of the ventricle within the chest and applying the linear attenuation coefficient of water (0.15/cm) (*5–8*) or the average of the linear attenuation coefficients of muscle, blood, and fat (0.16/cm) (*9*). Correcting for attenuation in this manner requires that two assumptions be valid: first, attenuation of the intervening structures must be identical to that of water (or body tissues); and second, attenuation of photons from the cardiac chambers must be uniform. Use of the linear attenuation coefficient of water (or body tissues) for these measurements assumes the presence of narrow-beam geometry and absence of scatter. In clinical applications of radionuclide ventriculography these conditions are not met. The usual, relatively wide windows that are employed accept a considerable number of Compton scattered photons. Furthermore, the large amount of air present in the chest may lower the average attenuation of photons from the heart. Accordingly, the narrow beam attenuations of water and body tissues may cause overestimation of ventricular volumes. Chest wall attenuation studies using radionuclide sources in the esophagus (*10,11*), phantom studies (*12, 13*), and calculations from transmission computerized

Received Dec. 2, 1985; revision accepted June 19, 1986.

For reprints contact: Gregory J.Dehmer, MD, Director, Cardiac Catheterization Laboratory, VA Medical Center, 4500 South Lancaster Rd., Dallas, TX 75216.

The results of this work were reported in part at the meeting of The Society of Nuclear Medicine, June 2–5, 1985, in Houston, TX, and were published in abstract form (*J Nucl Med* 1985; 26:P42).

tomography (*14*) have indicated that chest wall attenuation in cardiac blood-pool imaging is, in fact, considerably less than that predicted by the narrow beam attenuation coefficients for water and body tissues.

The purpose of this study was (a) to determine the attenuation of technetium-99m (^{99m}Tc) photons from a source within various intracardiac sites; (b) derive, as directly as possible, an average attenuation coefficient for cardiac ventricular volume determinations; and (c) to determine if attenuation from the cardiac chambers is uniform.

PATIENTS AND METHODS

Patients

Ten male patients referred for routine right and left heart catheterization comprised the study population. All were referred to evaluate coronary artery disease. The mean age was 55 yr, (range 39–61). Mean body surface area was 2.00 ± 0.27m^2 (range 1.62–2.66). Mean left ventricular end-diastolic volume (by biplane contrast angiography) was 209 ± 62 ml (range 132–320).

Study Protocol

To determine attenuation, a source of radioactivity was positioned at various known locations within the heart while the count rate was measured externally using an Anger camera. The count rate of the source was determined again after its removal from the body. Prior to this study, it was determined that the count rate of the source outside the body would not saturate the detection capabilities of the gamma camera. After correction for the isotopic decay that occurred between the two determinations, these values were used to calculate attenuation as outlined below.

Radionuclide Techniques

The radioactive source was produced by filling the balloon of a flow-directed catheter with ^{99m}Tc. In preparing the catheter, the following procedure was utilized. First, the balloon port was connected to a double stopcock manifold and was vigorously aspirated to remove air. Second, ~0.75 mCi of ^{99m}Tc in 0.75 ml of physiologic saline was drawn into a 3-ml syringe. Third, the 3-ml syringe was connected to the manifold and the balloon was inflated with isotope. To avoid loss of the ^{99m}Tc this connection was never broken until the study was completed. Finally, the balloon was inflated and deflated repeatedly to ensure adequate mixing of the radionuclide. Prior to beginning the study, we determined that the variation in balloon activity between different inflations was <5% and that 95.0 ± 3.2% (mean ± 1 s.d.) of the total activity from the catheter was contained within the inflated balloon.

The activity of the source in and out of the body was determined using a small field-of-view Anger camera with a general all-purpose collimator and a 20% window centered on the photopeak of ^{99m}Tc. In each balloon position, activity was measured three times for one min each, and the results averaged. Between each determination, the balloon was deflated and inflated. Correction for decay between measurements was accomplished using the standard decay formula $C(t) = C_0e^{-\lambda t}$, where $\lambda = 0.693/T_{1/2}$, $T_{1/2}$ for ^{99m}Tc is 360 min, C_0 is the counts at time zero, and C(t) is the counts at time t, the time between the counting periods.

The activity of the source was measured from the total counts in the Anger camera image. For counting in air, ~95% of the total counts were within a region of interest (ROI) drawn only around the image of the balloon; the remainder was explained by counts within the shaft of the catheter. Therefore, when activity of the balloon outside the body was determined, no correction for scatter was made. When the activity of the balloon inside the body was determined, correction for scatter was necessary. To evaluate the effect of scatter on these measurements, five additional patients underwent imaging and analysis using an image processing computer. Activity in the ROI around the balloon was 81.2 ± 6.5% of the total counts in the image. The values for the right and left ventricles respectively were 82.3 ± 9.3% and 80.2 ± 3.5%. There were no significant differences between the right and left-sided values among the patients. Therefore, the total counts from the balloon in the body for the ten patients of this study were multiplied by 0.81 to correct for scatter. For all views acquired with the balloon in the body, the camera face was positioned parallel to the floor while the patient was rotated into a 35° left anterior oblique (LAO) position in the

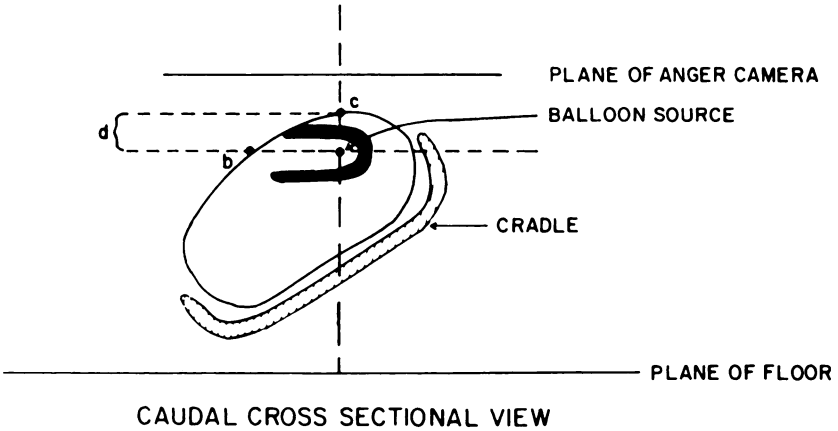

FIGURE 1
Technique for determining the tissue depth (d) is depicted in this transverse figure as seen from the feet. The collimator of the Anger camera is positioned parallel to the floor and the patient was rotated to a 35° LAO position with respect to the collimator surface. Without changing patient rotation, fluoroscopy was used to locate the position of the balloon source in the heart in the anteroposterior plane and the skin marked (point c). In a similar fashion, fluoroscopy was used to locate the source in the lateral plane and the skin marked (point b). The tissue depth (d) was measured as the vertical distance between points c and b.

x-ray cradle as described below. The collimator was lowered to just make contact with the skin prior to imaging. When counting the balloon in air, the collimator was positioned 5 cm from the source using the same technique that has been employed for positioning a blood-filled plastic syringe during ventricular volume analysis of the radionuclide ventriculograms (*2,5*).

Catheterization Techniques

As part of the routine catheterization, the femoral artery and vein were cannulated with a hemostatic sheath. Using these access sites and fluoroscopy, the tip of the catheter was advanced to four different intracardiac locations: (a) the junction of the inferior vena cava and right atrium, (b) the right ventricular apex, (c) the aortic root just above the aortic valve, and (d) the left ventricular apex. These locations were chosen because they were stable positions for the catheters, easily reproducible, and approximated the limits of the long axes of both ventricles. In each location, the balloon was inflated and imaged as described above and the depth within the body determined. Tissue depth was determined using biplane fluoroscopy (Fig. 1). With the patient remaining in the same LAO position as used for the radionuclide image, the location of the balloon was determined with anteroposterior fluoroscopy and marked on the skin. In a similar manner, the balloon position was determined with lateral fluoroscopy and marked externally. The vertical distance between these marks (tissue depth) was measured with a radiologic caliper.

Theoretical Considerations and Statistical Analysis

In order to calculate the attenuation of tissue, several variables must be known. The equation for the attenuation of photons is:

$$A = A_0 e^{-\mu d}, \quad (1)$$

where Ao is the unattenuated activity, A is the attenuated activity, μ is the attenuation coefficient of the attenuating medium and d is the distance through the attenuating medium. This equation assumes that μ is constant throughout the distance of the attenuating medium. In this study, A is the activity of the source within the heart, Ao is the activity of the source outside the body and d is the depth of the source within the body.

Equation 1 can be rearranged to the form:

$$\ln \frac{A_0}{A} = -\mu d. \quad (2)$$

Although attenuation can be expressed as a number <1 (the ratio of A to Ao), in this paper results are presented by plotting the values of the natural logarithm of Ao/A on the vertical axis, and the distance d on the horizontal axis. In this format, the slope of the line is μ, the attenuation coefficient. The

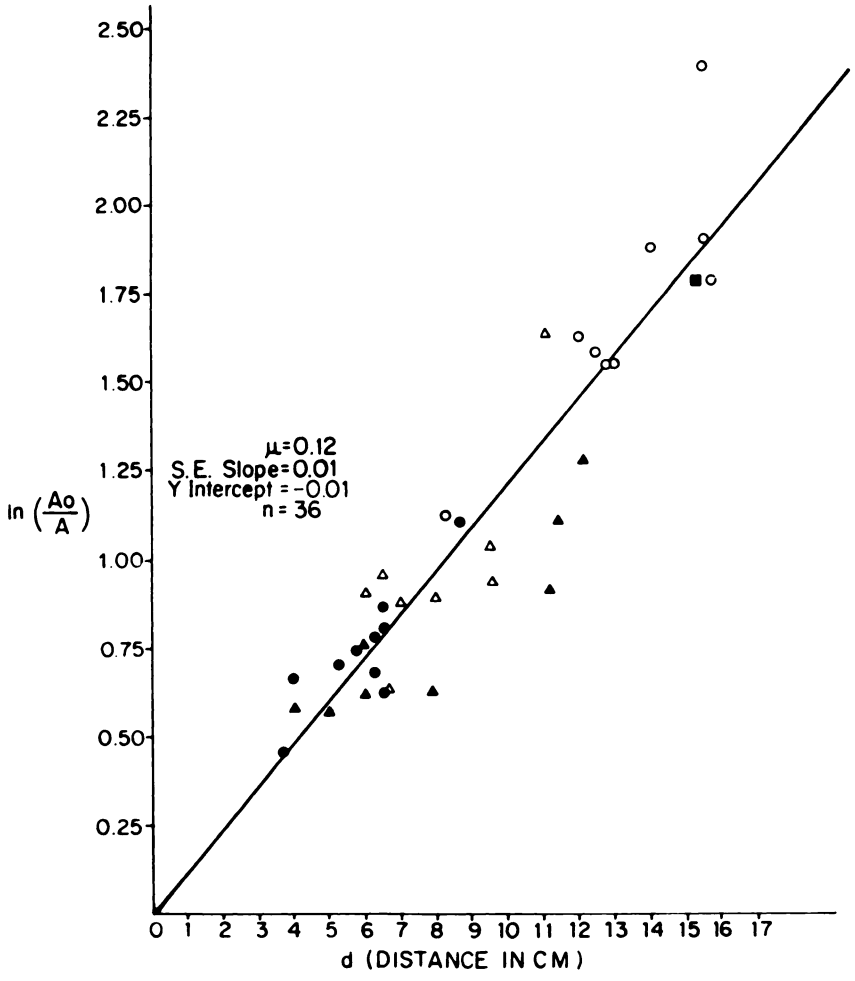

FIGURE 2
Relationship between the tissue depth (d) in centimeters (horizontal axis) and the natural logarithm of unattenuated activity (Ao)/attenuated activity (A). All 36 measurements are plotted in this figure. Closed circles (●) represent values from the right ventricular apex, open circles (○) values from the right atrial/inferior vena cava junction, closed triangles (▲) values from the left ventricular apex, open triangles (△) values from the above aortic valve and a closed square (■) the value from the left atrium.

relationship of the natural logarithm of the quotient (Ao/A) versus the respective distance, d, was tested with least squares linear regression. A p value of <0.05 was considered significant. Group comparisons of μ values from the different intracardiac locations was performed with a Newman-Keuls multiple comparison analysis.

RESULTS

In the ten patients studied, a total of 36 measurements of attenuation were obtained. The 36 measurements included ten from the right ventricular apex, eight from the left ventricular apex, nine from the right atrial/inferior vena caval junction, eight from the aortic root just above the aortic valve and one from the left atrium entered through a patent foramen ovale. In two patients the catheter could not be manipulated around the aortic arch; thus measurements above the aortic valve and at the left ventricular apex could not be obtained.

The relationship between the natural logarithm of Ao/A and d for all 36 measurements is depicted in Figure 2. The slope of this relationship, μ, was 0.12/cm ($R = 0.93$; $p < 0.001$), the standard error of the slope was 0.01, and the y intercept was −0.01.

The results of linear regression analysis for each intracardiac location (right and left ventricular apices, aortic root just above the aortic valve, and the inferior venal caval/right atrial junction) and all left-sided and all right-sided locations are shown in Table 1. There was a significant linear relationship in every case. The lowest value for μ, 0.08 ± 0.02 cm, was determined for the left ventricular apex. The highest value, 0.13 ± 0.03 cm, was found for the inferior vena caval/right atrial junction. There was, however, no significant difference in the values of μ among the four specific intracardiac sites. The value of μ for all left-sided locations was 0.10 ± 0.02/cm and for all right-sided locations was 0.13 ± 0.01/cm; this difference was not significant.

TABLE 1
Linear Regression Results from Different Cardiac Locations

Balloon location	n[§]	y-intercept	μ	s.e. of μ[¶]	Correlation coefficient R[¨]	P[††]
RV[*] apex	10	0.14	0.10	0.02	0.86	=0.001
LV[†] apex	8	0.21	0.08	0.02	0.90	=0.002
Aortic root	8	0.02	0.12	0.04	0.76	=0.030
IVC/RA[‡] junction	9	0.04	0.13	0.03	0.85	=0.004
All right-sided	19	−0.02	0.13	0.01	0.97	<0.001
All left-sided	17	−0.12	0.10	0.02	0.85	<0.001
All	36	−0.01	0.12	0.01	0.93	<0.001

[*] RV = Right ventricular.
[†] LV = Left ventricular.
[‡] IVC/RA = Inferior vena caval/right atrial.
[§] n = Number of samples.
[¶] s.e. = Standard error.
[¨] R = Pearsons R value.
[††] P = Probability of null hypothesis.

DISCUSSION

In this study we have shown, by direct measurement, that the overall linear attenuation coefficient, μ, obtained with linear regression analysis of values from various locations within the right and left cardiac chambers is 0.12/cm, a value below the values of 0.15–0.16/cm that often have been used for absolute ventricular volume calculation. There is considerable indirect evidence that supports this finding. Fearnow et al. directly calculated μ for the chest wall in healthy young volunteers by placing a radioactive source within the esophagus (*11*). They determined that the average value for μ varied between 0.119/cm and 0.125/cm depending on imaging conditions, using a 20% window about the photopeak, as in the present study. Maurer et al. estimated attenuation by comparing the activity of a ^{99m}Tc-filled capsule located within the esophagus to the activity of the capsule outside the body in patients referred for cardiac catheterization (*10*). Images were recorded in the same left anterior oblique position used for the cardiac images and the average attenuation correction factor (ratio of unattenuated/attenuated counts) was 4.77. The depth of the esophagus was not reported in this study, but if this factor and the narrow beam attenuation coefficient of water is used, the average depth of the esophagus [from Eq. (1)] is calculated as 10.4 cm. If the average attenuation coefficient determined in the present work (0.12/cm) is used instead, the calculated esophageal depth is 13.0 cm which is more likely correct (Appendix A). Moreover, in their work, calculation of attenuation for each patient in this way resulted in ventricular volume measurements that correlated well with values obtained using contrast angiography. Nickoloff et al. calculated the thoracic attenuation coefficient for 12 patients using computerized axial tomography density numbers in a 40° LAO projection (*14*). They reported values of 0.129/cm from the center of the left ventricle and 0.135 from the esophagus. Guiteras et al., found that radionuclide right ventricular volumes in children determined by an attenuation corrected, count-based method correlated best with angiography when a value of 0.11/cm was used for the tissue attenuation coefficient (*15*). When 0.15/cm was used, the volumes were substantially overestimated by scintigraphy. A study using a point source of ^{99m}Tc at depths up to 18 cm in water-filled cylindrical phantoms gave the same value for μ, 0.12/cm, as in our study, when a 20% window was used (*13*).

Our data demonstrate that the attenuation coefficients derived from various locations within the heart

are only slightly different. The attenuation coefficients measured from the inferior vena caval/right atrial junction and the aortic root just above the aortic value are slightly, but not significantly, higher than those derived from the left and right ventricular apices. This variation is not unexpected. Previous studies have shown that for 140 keV photons the narrow beam attenuation coefficient for fat, muscle, and blood are 0.14/cm, 0.16/cm, and 0.17/cm, respectively, (*16*). In the left anterior oblique position used for these studies, the attenuation of these various tissues is integrated with the lesser absorption and Compton scattering caused by the air within the lung. Since photons coming from the right atrial/inferior vena caval junction and the aortic root pass through a greater amount of blood in the 35° LAO position, it is not unreasonable to expect that absorption and Compton scattering of photons will be greater per unit distance than from the ventricular apices. However, the differences in the attenuation coefficients from various intracardiac locations are small enough that they should not seriously interfere with use of an average attenuation value for the whole ventricular chamber.

There are several limitations to the interpretation of the present study. First, the locations of the source within the cardiac chambers is not ideal. When the balloon of the catheter was filled with the ^{99m}Tc mixture there was a strong natural tendency for it to settle at the apex of the ventricles. This was a stable position mechanically that did not cause dysrhythmias; thus, it was very suitable for imaging. The balloon position was not stable in the middle of the ventricles. Since the apices approximate the part of the ventricles nearest the chest wall and the other two positions approximate the opposite ends of the long axes of the ventricles, these locations should provide good reference points for the extremes of measurement. The ideal, albeit impractical solution, would be to determine the attenuation coefficient in each patient at multiple ventricular locations and use the average of these values. The present study suggests that if a universal attenuation coefficient is to be assumed rather than measured directly in each patient, then a value of 0.12/cm in adult males is a good approximation of the actual value. Second, the size of the intracardiac source of photons is a limitation, but no practical solution exists. Siegel et al. have shown that the amount of scattered radiation varies with the size of the source (*12*). In clinical radionuclide ventriculography, the entire chamber is the source which is several multiples greater in diameter than the size of the balloon used in this study. Future phantom studies or investigations with experimental animals might yield corrections for differences in scatter owing to differences between the size of the balloon and the ventricles. Third, there is insufficient information to quantify the relative contributions of absorption and scatter to the attenuation from the various intracardiac locations and to examine the effects of the ROI size on the contribution of scattered photons. Imaging with varying windows around the 140 keV photopeak and at the 103 keV photopeak could provide useful data for these purposes (*11,13*), but would have prolonged unacceptably the time of the cardiac catheterization. Fourth, we employed linear regression analysis to calculate μ. The plot of ln Ao/A for ^{99m}Tc has been shown to be exponential, with less attenuation at shallow distances (*12,13*). However, at depths of ~4 cm or more, the plot becomes linear. Our depth values ranged from 3.7 to 14.7 cm, with only one less than 4 cm. Accordingly, linear regression analysis as employed in this study should result in only a slight error in estimating of an average value for μ. Finally, our results may not be applicable to all patients and other imaging conditions. The 35° left anterior obliquity employed in this study is close to the usual projection that best separates the left from the right ventricle. Slightly different degrees of obliquity, at least from 30° to 45°, would probably not yield a μ value greatly different from the one determined at 35° (*11*). The value for μ determined in this study was obtained during quiet ventilation over several minutes, thus reflecting the average of many ventilatory cycles. Accordingly, this value should be appropriate for the usual study obtained during quiet ventilation, but may not be suitable for patients with abnormal ventilation (*11*). Moreover this study was performed in middle-aged men with known or suspected heart disease. Most were smokers, but none had severe pulmonary disease. Therefore, the value for μ determined in the present study should be applicable to the majority of male patients undergoing radionuclide angiography and should be preferable to one obtained in normal young volunteers. This value for μ may not be applicable, however, to the patient with markedly increased lung volume, chest wall deformity, or large breast mass.

The results of the present study identify concerns about studies which use an attenuation coefficient of 0.15/cm or 0.16/cm for the calculation of ventricular volumes and demonstrate an acceptable correlation between contrast angiographic and radionuclide volumes. It is possible that a second systematic and counterbalancing error was present in those studies (*5–8*). Several variables must be measured for the calculation of attenuation-corrected radionuclide volumes. The ventricular ROI must be accurately determined at end-systole and end-diastole. The activity of sample of blood must be determined and the distance that photons travel must be accurately measured. Therefore, possible factors that could have counterbalanced the use of an attenuation coefficient of 0.15–0.16/cm include: (a) underestimation of the left ventricular ROI, (b) excessive subtraction of background, (c) underestimation of the attenuating tissue distance, and/or (d) overestima-

tion of the intravascular activity. Of these possible factors, errors in the measurement of intravascular activity seems the least likely because this process is easily performed in a consistent manner.

In summary, our direct measurements support recent indirect measurements that an attenuation coefficient of 0.15/cm is too high for radionuclide ventriculography and could lead to overestimation of absolute ventricular volumes. Based on our data, a value of 0.12/cm seems appropriate for most adult male patients. Use of this value for μ needs confirmation in a larger series with careful attention to the potential systematic errors in ventricular ROI identification, background subtraction, and ventricular depth measurement that may occur.

APPENDIX A

In order to determine the average depth of the esophagus from the skin surface in a 35° LAO view we examined the calibrated transaxial views from 20 randomly selected transmission computerized axial tomographic scans obtained from the Radiology Department at the Dallas Veterans Administration Medical Center (excluding patients with obvious esophageal or mediastinal disease). The distance was measured at the transaxial level of the apex of the heart, from the center of the esophagus to the skin surface at a 35° LAO angle. The mean value was 14.7 cm (s.d. 1.5 cm, range 13–18 cm).

ACKNOWLEDGMENTS

The authors thank Donald Haagen, Janie McCoulskey, RN, Willie Gary, Graciela Fields, and Farris Hix for their technical help, and Shelia G. Kelley and Pauline Shirley for typing the manuscript.

REFERENCES

1. Slutsky R, Karliner J, Ricci D, et al. Left ventricular volume by gated equilibrium radionuclide angiography. A new method. *Circulation* 1979; 60:556–564.
2. Dehmer GJ, Lewis SE, Hillis LD, et al. Nongeometric determination of left ventricular volumes from equilibrium blood pool scans. *Am J Cardiol* 1980; 45:293–300.
3. Massie BM, Kramer BL, Gertz EW, et al. Radionuclide measurement of left ventricular volume: comparison of geometric and count-based methods. *Circulation* 1982; 65:725–730.
4. Dehmer GJ, Firth BG, Lewis SE, et al. Direct measurement of cardiac output by gated equilibrium blood pool scintigraphy: validation of scintigraphic volume measurements by a non-geometric technique. *Am J Cardiol* 1981; 47:1061–1067.
5. Links JM, Becker LC, Shindledecker JG, et al. Measurement of absolute left ventricular volumes from gated blood pool studies. *Circulation* 1982; 65:82–91.
6. Starling MR, Dell'Italia LJ, Walsh RA, et al. Accurate estimates of absolute left ventricular volumes from equilibrium radionuclide angiographic count data using a simple geometric attenuation correction. *J Am Coll Cardiol* 1984; 3:789–798.
7. Starling MR, Dell'Italia LJ, Nusynowitz ML, et al. Estimates of left-ventricular volumes by equilibrium radionuclide angiography: importance of attenuation correction. *J Nucl Med* 1984; 25:14–20.
8. Burow RD, Wilson MF, Heath PW, et al. Influence of attenuation on radionuclide stroke volume determinations. *J Nucl Med* 1982; 23:781–785.
9. Petru MA, Sorenson SG, Chaudhuri TK, et al. Attenuation correction of equilibrium radionuclide angiography for non-invasive quantitation of cardiac output and ventricular volumes. *Am Heart J* 1984; 107:1221–1228.
10. Maurer AH, Siegel JA, Denenberg BS, et al. Absolute left ventricular volume from gated blood pool imaging with use of esophageal transmission measurement. *Am J Cardiol* 1983; 51:853–858.
11. Fearnow EC, Jaszczak RJ, Harris CC, et al. Esophageal source measurement of Tc-99m attenuation coefficient for use in left ventricular volume determinations. *Radiology* 1985; 157:517–520.
12. Siegel JA, Wu RA, Maurer AH. The buildup factor: effect of scatter on absolute volume determination. *J Nucl Med* 1985; 26:390–394.
13. Harris CC, Greer KL, Jaszczak RJ, et al. Tc-99m attenuation coefficients in water-filled phantoms determined with gamma cameras. *Med Phys* 1984; 11:681–685.
14. Nickoloff EL, PermanWH, Esser PD, et al. Left ventricular volume: physical basis for attenuation corrections in radionuclide determinations. *Radiology* 1984; 152:511–515.
15. Guiteras P, Green M, Desouza M, et al. Count-based scintigraphy method to calculate ventricular volumes in children: in vitro and clinical validation. *JACC* 1985; 5:963–972.
16. Phelps ME, Hoffman EJ, Ter-Pogossian MM. Attenuation coefficients of various body tissues, fluids and lesions that photon energies of 18-23 keV. *Radiology* 1975; 117:573–583.