Left Ventricular Volume Measurement Using Cardiac Axis Nuclear Magnetic Resonance Imaging

Validation by Calibrated Ventricular Angiography

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Proton nuclear magnetic resonance (NMR) imaging has the potential to serially assess left ventricular (LV) volumes with optimal accuracy because it is a high-resolution, three-dimensional, noninvasive modality. Previous NMR studies to assess LV volumes have been suboptimal, as they have used either planes aligned with the axes of the body, which are compromised by partial volume effects, or spin-echo techniques that have been time-consuming to acquire and analyze. Accordingly, for LV volume measurement, we developed a gradient-echo (cine) NMR strategy that uses two orthogonal planes intersecting along the intrinsic long axis of the heart (two-chamber and four-chamber). This approach was validated against calibrated contrast biplane LV cineangiography (CATH) and also compared with a previously reported short-axis spin-echo NMR method. Twenty-one patients underwent CATH and NMR (long-axis, n=21; short-axis, n=14) within a 3-day interval. Although both long- and short-axis NMR LV volumes and ejection fractions correlated well with CATH (r>0.90, p<0.001 in all), end-diastolic volumes by both long-axis (161±85 ml) and short-axis (151±81 ml) NMR were systematically less than those by CATH (182±85 ml) (p<0.05). Consequently, ejection fractions by long-axis (48±17%) and short-axis (49±17%) NMR consistently underestimated those by CATH (54±16%, p<0.05). End-systolic volumes by long-axis (94±71 ml) and short-axis (87±72 ml) NMR were not significantly different from those by CATH (92±69 ml). Both NMR techniques had low intraobserver and interobserver variation (<11%); however, short-axis spin-echo NMR involved longer acquisition/reconstruction (35 versus 18 minutes) and analysis (25 versus 10 minutes) times. We conclude that both short-axis spin-echo and long-axis gradient-echo NMR approaches reliably estimate LV volumes. Currently, the long-axis strategy appears more practical for clinical use because the scan and analysis times are relatively short. (Circulation 1990;82:154–163)

Assessment of left ventricular (LV) function is important in determining diagnosis, management, and prognosis in patients with cardiac diseases. This has been accomplished, noninvasively, by measuring the LV ejection fraction (EF). However, it has been shown that the LV end-systolic volume (ESV) may be a better predictor of systolic function and prognosis in patients with valvular regurgitation1 or after myocardial infarction.2

Clinical use of LV volumes has not been widely accepted because of a lack of practical and reliable noninvasive methods for quantitation. Radionuclide techniques are subject to unpredictable attenuation factors that vary from patient to patient and may change after surgery. Echocardiography is operator dependent and may suffer from poor acoustic windows and inadequate discrimination of the endocardial border in many patients.

Nuclear magnetic resonance (NMR) imaging is a relatively new imaging modality that does not require contrast agents or use ionizing radiation. The high spatial resolution of NMR imaging has been demon-
strated in studies that show the accuracy of this technique for measuring cardiac dimensions.\textsuperscript{3-7} Preliminary studies have demonstrated the potential of NMR imaging for assessing LV volumes.\textsuperscript{8-14} These studies have used either imaging planes aligned with the axes of the body\textsuperscript{9,12,13} rather than the intrinsic axes of the heart, or spin-echo pulse sequences that require long acquisition times.\textsuperscript{8-12,14}

The current standard for LV volume measurement is radiographic contrast LV cineangiography (CATH). Only one previous NMR study has reported validation of LV volume measurements against CATH in an acceptable number of patients (\(n=24\)).\textsuperscript{10} The authors of this study commented, however, that their results were “without immediate clinical utility” as the acquisition times were extremely long (up to 60 minutes) for either of the spin-echo strategies that they used.

The recent introduction of gradient-echo pulse sequences,\textsuperscript{15} with rapid pulse repetition times, markedly improves temporal resolution and has the potential to reduce acquisition times. With this sequence, the blood pool has increased signal intensity, permitting clear contrast with the myocardium. In addition, it is now possible to perform angulated imaging in any tomographic plane of the body without moving the patient.

Accordingly, using the gradient-echo sequence, we developed an imaging approach for assessing global and regional LV function that can be performed in less than 30 minutes. This method is based on acquiring two perpendicular tomographic planes that intersect along the intrinsic long axis of the left ventricle. This strategy was validated in 21 patients by comparison with calibrated CATH studies. In 14 of these patients, a multiple-slice, short-axis spin-echo technique was also compared with the long-axis NMR strategy and CATH.

This article reports the first validated study that combines the theoretical advantages of intrinsic cardiac axis imaging with the practical advantages of the gradient-echo technique.

\textbf{Methods}

\textit{Patient Population}

Patients undergoing routine cardiac catheterization were screened for eligibility for the study. Many patients could not be included for logistic reasons (i.e., patients undergoing early coronary angioplasty or coronary artery bypass surgery or patients who could not be scheduled for an NMR study within 72 hours). Other exclusion criteria were recent myocardial infarction or hemodynamic instability, recent change in medications, atrial fibrillation, implanted pacemaker, metallic prosthetic valves, and metallic cerebral aneurysm clips. Five patients were excluded also for technically inadequate CATH studies: arrhythmia during LV angiogram that precluded analysis (\(n=3\)), improperly positioned “cue ball” (\(n=1\)), and left ventricle too large (>500 ml) to be properly imaged without significant pincushion effects occurring (\(n=1\)).

Twenty-three patients satisfying the above criteria were studied by NMR within 72 hours of the cardiac catheterization. Subsequently, two of these patients were excluded, one because of claustrophobia and one because of poor-quality NMR study. This left 21 patients (age, 55±16; 10 female). Reasons for CATH were to assess coronary artery disease (\(n=15\), eight with history of previous myocardial infarction), valve regurgitation (\(n=2\), dilated cardiomyopathy (\(n=1\)), and postcardiac transplant evaluation (\(n=3\)). Informed consent was obtained from all patients before the study.

\textbf{Cardiac Catheterization}

Standard CATH\textsuperscript{16} (30° right anterior oblique [RAO] and 60° left anterior oblique [LAO] with 15° craniocaudal angulation, 8F pigtail catheter, 40–60 ml meglumine diatrizoate [Renografin-76, E.R. Squibb & Sons Inc., Princeton, N.J.]) was performed at 30 frames per second using a parallelogram system (Poly Diagnost C, N.V. Philips, Eindhoven, The Netherlands). For calibration, a cue ball (diameter, 5.6 cm) was screened in the exact position that the left ventricle had been during the ventriculogram (Figure 1). This was achieved by marking the position of the center of the left ventricle on both the RAO and LAO image intensifiers and then moving the cue ball until it lined up in both projections. This method has been validated using latex casts of postmortem ventricles.

Ventriculograms were traced by a single observer, who took care to avoid postectopic beats. Volumes were calculated using the standard Sandler-Dodge biplane method, which corrects for foreshortening of the LAO projection\textsuperscript{17,18}.
Volume = 8 \times CF_{\text{max}} \times A_{\text{RAO}} \times CF_{\text{RAO}} \times A_{\text{LAO}} \times CF_{\text{LAO}} / (3 \pi \times L_{\text{min}})

where A is area, L is the length of the long axis, and CF is the correction factor determined by planimetry of the cue ball. Practically, $CF_{\text{max}} = CF_{\text{RAO}}$, and $L_{\text{min}} = L_{\text{LAO}}$. A regression equation, based on the LV cast study (see “Appendix”), was then used to correct for overestimation of LV volumes due to papillary muscle and trabeculae inclusion, as well as the small pincushion effect present on this system:

Actual volume (ml) = 0.944 \times \text{CATH volume} - 1.3
(\text{r}=0.99, \text{SEE}=4.9 \text{ ml})

Long-Axis Cine Nuclear Magnetic Resonance Imaging

All NMR studies were performed on a 1.5 T imaging system (Philips Medical Systems, Shelton, Conn.). Two long-axis planes (two-chamber and orthogonal four-chamber) were acquired using cine NMR ($n=21$).

The two-chamber (RAO) is a single-angled plane perpendicular to the transverse (axial) plane. It is parallel to the septum and intersects the apex and mitral valve. Using the single-angled PLANSCAN software available on the imaging system, the line of intersection of the proposed plane with a scout series of transverse spin-echo images was visualized. The line of intersection was adjusted so that it passed through the apex on the inferior transverse slices and the mitral valve on the superior transverse slices. Fine adjustments in angulation and offsets were made to ensure that the plane was optimally aligned with both systolic and diastolic scout images.

The four-chamber is a double-angled plane, perpendicular to the two-chamber plane. Using the double-angled PLANSCAN software, it can be similarly aligned with sagittal and coronal scout images so that it intersects the apex and mitral valve and is perpendicular to the septum. To ensure that it was precisely perpendicular to the two-chamber plane, a personal computer program (THREE POINT PLANSCAN) specifically written for this purpose was also used. This program calculates the angles and offsets based on the knowledge that the four-chamber plane passes through the apex and the mitral valve (for which the three-dimensional coordinates can be obtained from the previous images) and is perpendicular to the previously determined two-chamber plane for which the angles and offsets are known.

Long-axis acquisition parameters (four measurements and 16 cardiac phases) were slice thickness, 8 mm; pulse flip angle, 45–50°; gradient-echo time, 12–14 msec; and resolution. $128 \times 128$ interpolated to $256 \times 256$ during reconstruction. Repetition time (32–50 msec) and acquisition/reconstruction time (mean, 9 minutes per view) varied with heart rate (84 ± 17). The total time for acquiring the long-axis scans including the scouts was 25–30 minutes.

For volume determination, end-diastolic and end-systolic frames were determined from the cinematic display. The LV area and length were determined on-line by an experienced observer using a tracker ball (Figure 2). Long-axis NMR volumes were calculated using the same Sandler-Dodge biplane formula as for CATH. For NMR, however, dimensional correction factors are not needed, as the calibration on the imaging system is regularly checked with standard phantoms and rarely requires adjustment. The equation thus simplifies to

Volume = \frac{8 \times A_2 \times A_4}{3 \pi \times L_{\text{min}}}

where $A_2$ is the two-chamber area, $A_4$ is the four-chamber area, and $L_{\text{min}}$ is the length of the shorter long axis. Note that this equation takes into account the possibility that one of the long axes may be foreshortened because of either imperfect alignment or excessive movement of the long axis during systole when the imaging plane is fixed.

Short-Axis Cine Nuclear Magnetic Resonance Imaging

In addition to the long-axis study, when system time permitted, a multislice, multiphase, short-axis spin-echo volume study was also performed (14 patients). Eight stacked slices were acquired perpendicular to the long axis and the ventricular septum, covering the left ventricle from apex to base. Scout images were used to determine the necessary angulations and offsets (Figure 3). This approach is
similar to a method previously reported by Pettigrew et al.20

Acquisition parameters (two measurements, eight slices, eight phases) were slice thickness, 10 mm; spin-echo time, 30 msec; repetition time, equal to RR interval; and resolution, 128x128 interpolated to 256x256 during reconstruction. Heart phase interval (50–60 msec) and acquisition/reconstruction time (mean, 35 minutes) varied with heart rate.

For volume determination, each slice was planimetered at end systole and end diastole, and volumes were calculated by summation (Simpson's rule). Determination of the most basal LV slice for inclusion in analysis was aided by cine display. This is necessary because the tomographic NMR plane remains fixed, whereas the ventricle shortens during systole with most of the translocation occurring in the basal slice (usually 1 cm).

Analysis

NMR and CATH volumes were compared using least-squares regression. Repeated-measures analysis of variance and the Student-Newman-Keuls test were used to determine if there were systematic differences in volume and EF estimation between the techniques. NMR and CATH analyses were performed by independent blinded investigators. For interobserver error determination, volumes were analyzed by a further independent investigator. For determination of intraobserver error, studies were reanalyzed by the same independent investigator. For determination of intraobserver error, studies were reanalyzed by the same observer after at least 3 months, with the observer blinded to the original results. Observer error for volume determination was calculated as the mean coefficient of variation, which expresses the variation as a percentage of the absolute volumes. For EF, errors were expressed as the mean difference in observations.

Results

Regression data for long- and short-axis NMR versus CATH are shown in Table 1 and Figures 4-6. Mean volumes±SD for patients who underwent both

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**Figure 3.** A short-axis plane (right panel) aligned perpendicular to the long axis of the ventricle using software that permits double angulation. Left panel: line of intersection of a midventricular short-axis plane with a transverse scout image. Middle panel: line of intersection of the same short-axis plane with a coronal scout image. These lines of intersection are adjusted until the proposed plane is perpendicular to the septum and long axis of the left ventricle. Multiple slices are then selected so that the stack covers from the base to the apex.

**Figure 4.** Left ventricular end-diastolic volume (ml); correlation between long- and short-axis nuclear magnetic resonance (NMR) and biplane left ventricular cineangiography (CATH).
short- and long-axis NMR studies \((n=14)\) are shown in Table 2 and Figure 7.

**Biplane Long-Axis Cine Nuclear Magnetic Resonance Versus Cineangiography**

End-diastolic volume (EDV) by NMR correlated well with but appeared to consistently underestimate that by CATH \((r=0.93, \text{SEE}=31 \text{ ml}, p<0.001)\). ESV by NMR correlated well with that by CATH \((r=0.95, \text{SEE}=21 \text{ ml}, p<0.001)\). Similarly, EF by NMR correlated well with CATH but consistently underestimated CATH because of the underestimation of EDV \((r=0.93, \text{SEE}=6\%, p<0.001)\).

**Short-Axis Nuclear Magnetic Resonance Versus Cineangiography**

Results for short-axis NMR were similar to those for long-axis NMR, with EDV, ESV, and EF correlating well with CATH \((r>0.90)\). Again, both EDV and EF by NMR appeared to underestimate EF by CATH.

**Systematic Differences Between Methods**

For the 14 patients who underwent both long- and short-axis NMR studies, repeated-measures analysis of variance was performed to determine if there were any systematic differences between the techniques. EDV by both long-axis \((161±85 \text{ ml})\) and short-axis \((151±81 \text{ ml})\) NMR was found to underestimate CATH \((182±85)\) \((p<0.05)\); however, ESV by long-axis \((94±71 \text{ ml})\) and short-axis \((87±72 \text{ ml})\) NMR did not significantly differ from CATH \((92±69 \text{ ml})\). Differences in EF paralleled differences in EDV, with EF by long-axis \((48±17\%)\) and short-axis \((49±17\%)\) NMR underestimating EF by CATH \((54±16\%)\) \((p<0.05)\). Short- and long-axis NMR measurements did not differ significantly from each other.

**Analysis Time**

With experience, the mean analysis time was reduced to 25 minutes for the short-axis studies and...
TABLE 1. Regression Data for Cineangiography (CATH) Versus Nuclear Magnetic Resonance

<table>
<thead>
<tr>
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<th>NMR</th>
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<tr>
<td></td>
<td>Long-axis (n=21)</td>
</tr>
<tr>
<td>EDV (ml)</td>
<td>0.93 (31 ml)</td>
</tr>
<tr>
<td>ESV (ml)</td>
<td>0.95 (21 ml)</td>
</tr>
<tr>
<td>EF (%)</td>
<td>0.93 (6%)</td>
</tr>
</tbody>
</table>

Correlation coefficients, p<0.001 in all; standard error of estimate in parentheses.
NMR, nuclear magnetic resonance; EDV, end-diastolic volume; ESV, end-systolic volume; EF, ejection fraction.

10 minutes for the long-axis NMR studies. The short-axis studies were considerably more difficult to analyze because of the increased blood signal in some of the images and, therefore, poorer contrast with the endocardium.

Observer Variation

Observer errors are shown in Table 3. The mean coefficient of variation was less than 11% for all volumes by either NMR technique. For EF analysis, the mean absolute difference in observations was less than 8% for both NMR techniques. The largest difference (7%) was observed with the NMR short-axis EF measurement. Most of the variation between observers for the NMR short-axis analysis was due to differences in defining and measuring the basal LV slices during systole and diastole. Observer errors were similar for CATH parameters, except that interobserver errors tended to be greater for CATH-determined volumes.

Discussion

Clinical Importance of Left Ventricular Volumes

Systolic ejection indexes such as EF have limitations in fully assessing LV function because of their dependence on loading conditions. ESV is independent of preload, although it may vary with afterload and may be a better predictor of outcome in patients with valvular regurgitation or after myocardial infarction. To date, routine clinical measurement of LV volumes has not occurred because of the lack of a reliable noninvasive method for quantitation.

Noninvasive Techniques

Radionuclide methods can reliably estimate LVEF. Methods to assess LV volumes have been devised; however, the more reproducible count-based techniques suffer from errors due to uncertainty in determining attenuation factors.

Cardiac ultrasound permits real-time imaging in a variety of planes. Visualization of the endocardium in many patients is complicated by poor acoustic windows, especially in the long-axis views and in patients with small ventricles. Various formulas have been devised to estimate the LV volume from long-axis views; however, they are neither reliable nor reproducible in most patients.

Ultrafast computed tomography has been validated in a canine model for assessing LV stroke volume; however, this technique requires injection of radiopaque contrast medium and uses ionizing radiation and would need further validation in humans for measuring LV volumes.

Cardiac NMR is noninvasive, uses no ionizing radiation, and permits acquisition of highly detailed...
images with accurate dimensional resolution. Current acquisition software now permits angulated imaging in any tomographic plane without having to rotate the patient, as has been done previously. NMR therefore appears to be an ideal imaging modality for serially assessing global and regional LV function. Although several studies have demonstrated the potential of NMR for measuring LV volumes, most have been limited by long acquisition times, poor temporal resolution of end systole, and suboptimal image planes. Furthermore, only one study has attempted to validate an NMR technique against CATH in a large series of patients (n=24). The design of the present study sought to address these problems.

**Present Nuclear Magnetic Resonance Study**

In the present study, both long- and short-axis NMR LV volumes correlated well with volumes obtained by CATH (r>0.90 in all). Volumes and EF by long- and short-axis NMR correlated well, with no significant systematic differences being observed between the two strategies. However, NMR EDV by either technique was generally lower than that by CATH, and consequently, NMR EF was consistently lower than by CATH. It is interesting that an underestimation of EF by NMR has also been noted in previous studies using a variety of different strategies. Several possibilities could explain these findings.

First, it is possible that the CATH technique overestimates the true EDV. This may be due to uncertainty in defining the LV border at end diastole, which may be less clear than at end systole. In these cases, the outer contour is usually drawn. Furthermore, the LV angiogram is a projection, which displays the maximum profile of the ventricle so that invaginations may not be accounted for. However, if this were the main reason, one would expect a similar problem to have occurred at end systole.

Second, it is possible that the NMR techniques underestimate the true EDV. With the gradient-echo approach, blood pool endocardial contrast depends on a “refreshment” effect (discussed below). This effect may be diminished when flow is very slow and predominantly in the imaging plane. It is possible that blood near the endocardium sometimes may not be optimally visualized at end diastole and that this may cause the slight underestimation of EDV by the gradient-echo long-axis NMR approach. Short-axis EDVs could be underestimated for a different reason. Imperfect alignment of the basal NMR tomograph could result in part of the left ventricle not being imaged at end diastole but being included at end systole as the base of the heart contracts toward the apex.

This study cannot determine which of these explanations is correct. NMR imaging is inherently a very accurate modality for measuring dimensions. It is possible that the small differences in EDV could be due to both an underestimation by NMR and an overestimation by CATH.

**Comparison of Pulse Sequences**

Spin-echo pulse sequences produce high-resolution images but have several disadvantages for assessing heart function. The blood pool generally has low signal intensity, except during slow flow when blood may have increased signal intensity, making discrimination of the blood pool/endocardial border difficult. When this occurs, border definition may be aided by a thin line of decreased signal intensity between blood and endocardium (due to a “shear effect”). However, in some of the short-axis slices, ambiguity in the LV endocardial border due to the blood signal and motion artifacts (increased at 1.5 T) could be overcome only by interpolation with the observer using “expert” knowledge about the likely shape of the ventricle. Furthermore, with spin-echo sequences, pulsing cannot occur more frequently than every 50 msec, and as 90° pulses are used, each slice can be pulsed only once each RR interval. This leads to prolonged acquisition times with only a limited number of phases.

The gradient-echo sequence circumvents the problems of long scan times, poor temporal resolution, and blood pool/endocardium discrimination. With this sequence, it is possible to pulse a slice every 25 msec (repetition time) and acquire a cine scan in less than 5 minutes if two measurements are used. Contrast between the blood pool and myocardium depends mainly on the relaxation state of the protons when they are excited. With the short repetition times used, static protons are excited repeatedly and become partially saturated, producing less signal. In contrast, protons, which rapidly move into the tomo-
graphic NMR slice (refresh), may be excited only once and thus produce a maximal signal. Consequently, the blood pool is generally of bright signal intensity because of refreshment of proton spins, whereas the myocardium is of lower signal intensity because of partial saturation of proton spins. These features and the rapid repetition times make the gradient-echo sequence more suitable for functional assessment.

Comparison of Imaging Planes

Three NMR imaging plane strategies have been described for LV volume measurement: transaxial, short-axis, and long-axis. The present study focused on the latter two intrinsic axis approaches.

Transaxial imaging. Most previous studies have used standard planes aligned with the body\(^6,12,13\) rather than with the heart. With this approach, slices transect the myocardium obliquely, leading to so-called partial volume effects.\(^5,7\) This may cause difficulty in planimetering the endocardial borders and also confounds concurrent assessment of wall motion.

Short-axis approach. The stacked short-axis approach has the theoretical advantage of encompassing the entire left ventricle and could provide clearer border definition when a gradient-echo sequence is used (multiple-slice gradient-echo imaging was not easily implemented when this study began).

However, for volume measurements, difficulty is often encountered defining the aortic and mitral valve planes, which may lie partially in the basal NMR slice and usually move at least 1 cm toward the apex during systole.\(^32\) Assumptions regarding the contour of the LV apex could also contribute to small errors in volume determination. Concurrent interpretation of regional LV function is also confounded with current short-axis approaches, because the myocardial slice moves, whereas the NMR imaging plane is fixed in space. Assessment of apical wall motion is impossible with this approach.

Long-axis approach. This approach avoids partial volume effects and requires fewer imaging planes, making acquisition and analysis times shorter. The valve planes and apex are well-defined; however, the use of a single long-axis plane is not sufficient in the presence of regional wall motion abnormalities.\(^14\) In these circumstances, the biplane approach used in the present study is theoretically more accurate for volume determination. Furthermore, for concurrent regional wall motion analysis, this approach permits adequate assessment of all segments, including the apex.\(^19\)

An assumption of this approach is that the long axis of the left ventricle does not change substantially between systole and diastole. This potential source of error was minimized by the technique used to align planes. The problems of the geometric assumption used in the Sandler-Dodge technique are well-known and are common to both the CATH and long-axis NMR methods.

Limitations of Study Design

CATH and NMR studies were performed within a 3-day time interval. The possibility of a change in LV volumes during this time was minimized by excluding patients with recent myocardial infarction, hemodynamic instability, or change in cardiac medications.

With all validation studies, there is always the problem of finding a suitable standard. CATH has been used for almost 30 years, and although it has several theoretical limitations, the method represents the best available technique for comparison. The use of the same algorithm (Sandler-Dodge) for both the CATH and long-axis NMR techniques would be expected to favor the present result.

Conclusion

Both the gradient-echo long-axis and spin-echo short-axis NMR strategies provide a reliable noninvasive means for determining LV volumes and EF. At present, reduced acquisition and analysis times make the long-axis technique more attractive; however, faster imaging times,\(^33,34\) improvements in edge-detection algorithms, and definition of the base of the heart may enhance the utility of the short-axis approach. The cost of NMR imaging is a potential disadvantage at present, but it can be expected to decline with improvements in the technology and the development of faster imaging sequences. Both techniques described in this study could serve as references for new NMR acquisition and processing methods, which may be developed in the future, without the need for further validation against cardiac catheterization.

Appendix

Determination of Left Ventricular Volumes by CATH

The “cue ball” technique described in “Methods” was chosen for this study because of the ability to position reliably the calibration object in the exact position the ventricle had been during the ventriculogram. In addition, a spherical object presents the same profile, regardless of the angle from which it is projected. This was an important consideration, because a 15° craniocaudal tilt is routinely used in our laboratory for the LAO projection. The size of the calibration object was chosen because the diameter (5.6 cm) represented the upper range of diameters of normal ventricles during diastole and the volume (92 ml) was in the range of ESVs in ventricles with impaired function.

Pincushion effects. Two studies were performed to assess pincushion effects on our catheterization laboratory imaging system. First, a standard grid was imaged in both the LAO and RAO projections, with the image intensifiers in the standard positions used in the patient studies. Varying sized areas on the grid were measured and normalized to the cross-sectional area of the cue ball (24.6 cm\(^2\)). Theoretical sphere volumes were then calculated based on the normalized areas measured. Using this approach, it was found that volumes less than the volume of the cue
ball are underestimated, whereas volumes larger than that of the cue ball are overestimated. For example, at a volume of 20 ml, there was a 3% underestimation, and at a volume of 385 ml, there was a 3.6% overestimation. However, at a volume of 550 ml, the measured error was 6.7%. The pincushion effect might be expected to follow an exponential relation; however, when volumes ranged from 20 to 385 ml, the errors were found to be small and closely predicted by the following linear regression equation:

True volume (ml) = 0.965 × CATH volume + 3.8

\( (r=0.99, \text{SEE}=2.1 \text{ ml}) \)

To further verify this finding, a second study was performed using the cue ball technique. Spherical objects of known volume (76–620 ml) were imaged in the isocenter of the system, using the method of alignment described in the text to position the cue ball for calibration (Figure 1). The image intensifiers were in the standard positions used for filming LV angiograms. The projected areas of the objects and the cue ball were planimetered and volumes calculated, using the cue ball to determine the correction factor. These results confirmed the previous “grid study,” in that, within the range of 76–455 ml, the error due to pincushion effects on our system is approximately linear and is shown as follows:

True volume (ml) = 0.968 × CATH volume + 0.7

\( (r=0.99, \text{SEE}=6 \text{ ml}) \)

At volumes greater than 500 ml, the error increases to greater than 6% and is not well predicted by linear regression.

**Left ventricular cast validation.** To derive an appropriate regression equation for LV volumes, eight casts of postmortem left ventricles were imaged. The image intensifiers were placed in the usual positions used for filming LV angiograms. The casts were positioned in the isocenter of the system so that the orientation was the same as it would be in vivo. The casts were then imaged and the cue ball subsequently positioned and imaged as described in the patient study (Figure 1). CATH-determined volumes were then compared with volumes by water displacement (range, 39–235 ml). The following correlation was obtained and subsequently used in the present study to correct the patient CATH volume measurements:

True volume (ml) = 0.944 × CATH volume − 1.3

\( (r=0.99, \text{SEE}=4.9 \text{ ml}) \)

This linear regression equation corrects for effects due to papillary muscles and trabeculae. It should also account for pincushion errors when ventricular volumes are less than 400 ml.

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