METHODS

Noninvasive Evaluation of Global Left Ventricular Function With Use of Cine Nuclear Magnetic Resonance

PETER T. BUSER, MD,* WOLFGANG AUFFERMANN, MD,* WILLIAM W. HOLT, MD, PhD,* STEPHAN WAGNER, MD,* BARBARA KIRCHER, MD,* CHRISTOPHER WOLFE, MD,‡ CHARLES B. HIGGINS, MD, FACC*
San Francisco, California and Basel, Switzerland

Previous reports have validated the accuracy of nuclear magnetic resonance (NMR) imaging for quantitating ventricular volumes and myocardial mass. In this study, a new rapid NMR imaging method, cine NMR imaging, was used to compare left ventricular volumes determined from the transverse plane and short-axis plane in healthy volunteers and patients with dilated cardiomyopathy. With use of the short-axis plane, left ventricular mass at end-systole and end-diastole were determined and left ventricular systolic wall thickening at three different levels was assessed. For validation in the current study, cine NMR imaging and two-dimensional echocardiographic measurements of left ventricular volumes were correlated.

Left ventricular volumes of the normal volunteers (end-systolic volume = 34 ± 3.8 ml, end-diastolic volume = 90.4 ± 7.2 ml) and patients with cardiomyopathy (end-systolic volume = 173 ± 28.3 ml, end-diastolic volume = 219.5 ± 29.6 ml) obtained in the transverse plane were nearly identical to those obtained in the short-axis plane (normal volunteers, end-systolic volume = 30.3 ± 3.5 ml, end-diastolic volume = 84.7 ± 7.0 ml and patients with cardiomyopathy, end-systolic volume = 179.1 ± 27.8 ml, end-diastolic volume = 227 ± 30.9 ml) and correlated highly (r = 0.91) with volumes obtained by two-dimensional echocardiography. Assessment of left ventricular mass over a broad range using cine NMR imaging in a short-axis plane was identical at end-systole (normal volunteers, 117 ± 10 g; patients with cardiomyopathy, 202 ± 20 g) and end-diastole (normal volunteers, 115 ± 10 g; patients with cardiomyopathy, 194 ± 21 g). Normal hearts exhibited a gradient of wall thickening increasing progressively from the base to the apex, whereas cardiomyopathic ventricles showed no gradient in the extent of wall thickening.

Thus, cine NMR imaging of the heart in a short-axis plane provides for the comprehensive geometric and functional evaluation of the normal and diseased left ventricle. The plane of imaging is not critical for the quantitation of ventricular volumes.

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be minimized (3,7). Indeed, it has been argued that the marked heterogeneity of wall thickening in the normal ventricle may result, in part, from inaccuracies due to oblique transsection of the left ventricular wall (8) and uncertainties in reliable identification of the endocardium (9). On the other hand, studies of the normal left ventricle in humans and animals (9–13) have shown a variability in segmental contraction comparing basal and apical regions.

Accordingly, the purposes of the current study were to 1) compare left ventricular volumes determined from transverse images with short-axis images; 2) compare the extent of wall thickening at basal, midventricular and apical regions of the left ventricle; 3) determine if the gradient in wall thickening dynamics is different for a dilated hypocontractile left ventricle than for a normal ventricle; and 4) compare left ventricular mass in normal subjects and patients with dilated cardiomyopathy.

Methods

Study subjects. The study group included 10 normal volunteers (aged 20 to 39 years) and 10 patients with dilated cardiomyopathy (aged 40 to 68 years). The diagnosis of congestive cardiomyopathy was based on clinical information and two-dimensional echocardiographic findings. The study was approved by the Human Research Committee at the University of California, San Francisco, and all subjects gave informed consent.

Imaging technique. Cine NMR imaging was performed with a commercially available 1.5 superconducting magnet (General Electric). Cine NMR imaging employs a flip angle of 30° and gradient refocused echoes with an echo time (TE) of 12 ms and a repetition time (TR) of 21 ms. In contrast to electrocardiographic (ECG)-gated spin-echo imaging, the ECG signal is simultaneously recorded and stored in a microcomputer, which controls advancement of the phase-encoding gradient with each R wave. The number of time frames per cardiac cycle corresponded to the number of repetition time intervals, which could be fitted into the RR interval of the ECG up to a fixed maximum. Two or three levels with a slice thickness of 10 mm were scanned simultaneously, resulting in 14 to 24 frames per heartbeat for each slice and a time resolution of 42 to 66 ms in patients with a heart rate of 60 to 100 beats/min.

A multislice, coronal, ECG-gated localizing sequence (imaging time 2 to 3 min) was used to identify the inferior extent of the heart. The first transverse cine series was started at this anatomic level and the whole heart was covered with 10 to 12 levels up to the bifurcation of the pulmonary artery, corresponding to four to six cine series. Additional localizing sequences determined the left ventricular long-axis angulation in the Y and Z imaging plane and from images in this plane, the short-axis plane was defined (perpendicular to the long axis of the left ventricle). The left ventricle was then covered from the apex to the base in a short-axis view with 8 to 12 slices of 10 mm thickness corresponding to four to six cine series.

Image analysis. For analysis, images were displayed on the computer monitor in a cinematic format. The frames showing the maximal (end-diastolic) and minimal (endsystolic) left ventricular cross-sectional areas at the midventricular level were then visually determined. The midventricular slice was defined by the total number of slices encompassing the left ventricle from the apex to the base divided by two. The slices 20 mm above and below this level were used as basal and apical slices, respectively. For each anatomic level inner (endocardial) and outer (epicardial + right septal edge) circumferences of the left ventricle were outlined with a track ball cursor and left ventricular cavity area and myocardial area were measured. The distinction between the left ventricle and the left atrium was facilitated in the transverse plane by the clearly visible insertion points of the mitral valve and in the short-axis plane by the visibility of the total circumference of the aortic root.

Left ventricular volumes were calculated as the sum of the cavity area times slice thickness of all slices covering the left ventricle. Mean cavity radius at a specific anatomic level was calculated as the square root of cavity area divided by π. Left ventricular mass was calculated as the sum of the myocardial area times slice thickness of all slices covering the whole left ventricle (Fig. 1) times specific myocardial gravity (= 1.05).

Mean left ventricular wall thickness at the basal, midventricular and apical level was assessed by the following method: A line was drawn from the junction point of the anterior epicardium with the outer left ventricular circumference to the most distant point of the inferior epicardium. The midpoint between these two points was assumed as center of the left ventricle. From this center the entire left ventricle was divided into eight sectors of 45° (Fig. 2). In each sector the minimal distance between the endocardium and the epicardium was measured to avoid inclusion of papillary muscle or trabeculation, or both; the procedure was done at end-systole and end-diastole. Percent systolic wall thickening of each sector was calculated as the difference of systolic minus diastolic wall thickness divided by diastolic wall thickness. The mean value ± SEM of percent systolic wall thickening of all eight sectors at each anatomic level was calculated.

Validation of volume measurements. Twenty-five left ventricular volumes were analyzed independently by two observers to define interobserver variability for a range of left ventricular volumes.

Echocardiography. Six healthy volunteers and eight patients with cardiomyopathy had two-dimensional echocardiographic studies of sufficient quality to permit clear recognition of the endocardial border to obtain the determinants...
for calculation of left ventricular end-systolic and end-diastolic volumes. The technique used to calculate volumes from two-dimensional echocardiographic studies has been described in detail previously (14). Briefly, the technique used measurements obtained from two views: short-axis views from the precordial window and long-axis views from the apical window. Volumes were calculated with use of a biplane Simpson algorithm (14). An average of three measurements was taken.

Statistical analysis. Left ventricular volumes obtained in transverse and short-axis plane and left ventricular mass obtained at end-systole and end-diastole by cine NMR imaging were compared with the paired t test (15) and linear regression analysis. Linear regression analysis was also used to define interobserver variability for left ventricular volumes and the correlation of left ventricular volumes obtained by cine NMR imaging and two-dimensional echocardiography. Scheffé’s test for multiple contrasts was applied to detect significant differences between the two study groups by the analysis of variance (15). The null hypothesis was rejected at the 95% confidence level considering a p value <0.05 as significant.

Results

Left ventricular volumes. The values for left ventricular end-systolic and end-diastolic volumes and left ventricular ejection fraction in normal subjects and patients with cardiomyopathy are presented in Table 1. There was no significant difference between the values obtained in the transverse and short-axis imaging plane except for end-systolic volumes in the normal control group (p < 0.02), where the values obtained in the short-axis view tended to be slightly smaller than those in the transverse imaging plane. Left ventricular end-systolic and end-diastolic volumes were significantly larger (p < 0.005) and left ventricular ejection fraction significantly lower (p < 0.001) in the cardiomyopathic group than in the normal control group.

The correlation of left ventricular volumes and ejection fraction between the transverse and short-axis planes is shown in Figure 3. Interobserver variability for measurements of left ventricular volumes was small (Fig. 4). The correlation between cine NMR imaging and two-dimensional echocardiography was high, although volumes calculated by echocardiography tended to be systematically larger (Fig. 4).

Left ventricular mass. Left ventricular mass was significantly larger (p < 0.002) in the patients with cardiomyopathy than in the patients with a normal heart (Fig. 5). There was no significant difference between the values obtained at end-systole and end-diastole in either group. The correlation between left ventricular mass obtained at end-systole and end-diastole was r = 0.99, SEE = 3.3 g in the normal group and r = 0.97, SEE = 15.9 g in the cardiomyopathic group.

Left ventricular systolic wall thickening. In normal hearts mean left ventricular systolic wall thickening increased continuously and significantly from the base to the midventricular level (p < 0.01) and from the midventricular to the apical level (p < 0.02) (Fig. 6A). In cardiomyopathic hearts
there was no significant increase of systolic wall thickening from base to apex. Compared with findings in normal hearts, mean systolic wall thickening was diminished significantly at the midventricular (p < 0.01) and apical (p < 0.01) levels in cardiomyopathic hearts. When the mean end-diastolic left ventricular radius at each anatomic level was compared in the two groups, this effect was even more pronounced and reached statistical significance also at the basal level (Fig. 6B).

Table 1. Left Ventricular End-Systolic (LVESV) and End-Diastolic Volumes (LVEDV) and Ejection Fraction (LVEF) Obtained in a Transverse and Short-Axis Imaging Plane in 10 Healthy Volunteers and 10 Patients With Dilated Cardiomyopathy

<table>
<thead>
<tr>
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<th>LVESV (ml)</th>
<th>LVEDV (ml)</th>
<th>LVEF (%)</th>
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<tbody>
<tr>
<td>Normal Transverse</td>
<td>34.9 ± 3.8</td>
<td>90.4 ± 7.2</td>
<td>61.9 ± 2.0</td>
</tr>
<tr>
<td>Normal Short axis</td>
<td>30.3 ± 3.5*</td>
<td>84.7 ± 7.0</td>
<td>64.3 ± 2.5</td>
</tr>
<tr>
<td>Cardiomyopathy Transverse</td>
<td>173.5 ± 28.3†</td>
<td>219.5 ± 29.6†</td>
<td>24.1 ± 3.7†</td>
</tr>
<tr>
<td>Cardiomyopathy Short axis</td>
<td>179.1 ± 27.8†</td>
<td>227.7 ± 30.9†</td>
<td>23.5 ± 3.1†</td>
</tr>
</tbody>
</table>

*p < 0.02 for transverse versus short axis plane; †p < 0.001 for normal versus cardiomyopathy; ‡p < 0.005 for normal versus cardiomyopathy.

Discussion

Cine nuclear magnetic resonance imaging. Nuclear magnetic resonance imaging of the heart produces distinct visualization of the endocardial and epicardial edges of the myocardium. Because it is a noninvasive and inherently three-dimensional imaging technique, any desired imaging plane of the heart may be depicted. This makes the projection of a true short-axis view of the left ventricle possible by
measuring left ventricular long-axis deviation in the Y and Z planes and defining the respective plane perpendicular to this axis. The fast imaging pulse sequence called cine NMR imaging provides an adequate time resolution necessary for the evaluation of the temporal geometric changes of the entire left ventricle throughout the cardiac cycle.

Like all cross-sectional imaging modalities, cine NMR imaging is affected by partial volume averaging, although previous studies (2-7,16-21) have documented the reliability and reproducibility of right and left ventricular dimensions and volumes in a transverse or left ventricular long-axis plane. It has been postulated that measurement inaccuracies introduced by transverse sections orthogonal to the body axis could be diminished by imaging the heart in sections orthogonal to the intrinsic heart axis (3,7). Therefore, left ventricular volumes and ejection fraction measured in transverse and short-axis imaging planes were compared in the current study.

**Imaging planes.** Left ventricular volume measurements were nearly identical in transverse and short-axis imaging planes in subjects with a wide range of left ventricular dimensions. Therefore, partial volume effects may have affected both transverse and short-axis volume measurements similarly. The correlation of measurements of left ventricular volumes obtained by cine NMR imaging in a short-axis view and two-dimensional echocardiography was...
in the range of previously reported results (2,3,16,21). Volume calculations by two-dimensional echocardiography tended to be systematically larger than volume measurements by cine NMR imaging. The partial inclusion of papillary muscle to the cavity volume in two-dimensional echocardiography may account for this difference. Cine NMR imaging has the distinct advantage over two-dimensional echocardiography to be independent of geometric assumptions for volume determinations.

Left ventricular mass. Several studies (22-23) in animals have shown that NMR imaging can accurately measure left ventricular mass in vivo. Imaging of the myocardium in a short-axis plane may provide the ideal method for this measurement (22). Despite an overall underestimation due to partial volume effects this method has been shown to correlate highly with postmortem weights of the left ventricle (22). In healthy volunteers mean left ventricular mass was in the lower range of previously reported postmortem and angiographic values (26,27). In this group the much lower mean age and, to a minor degree, partial volume effects may have contributed to the lower values for ventricular mass in the current study. Measurements of left ventricular mass over a broad range in a short-axis view obtained with cine NMR imaging at end-systole and end-diastole were nearly identical. However, measurements at end-diastole may be easier to obtain, because contrast between flowing blood in the ventricular cavity and the adjacent myocardium is higher at this phase of the cardiac cycle.

Left ventricular wall thickness and thickening. In a short-axis imaging plane the left ventricular wall and the interven- tricular septum are cut perpendicularly, thereby providing a true wall thickness at a basal and midventricular level. However, approaching the apex, this plane might have sectioned the walls with increasing obliquity due to the ellipsoid shape of the left ventricle. This may be even more pronounced during systole because of the shortening of the left ventricle along its long axis. Therefore, left ventricular wall thickness and systolic wall thickening may have been overestimated at the apical level especially in hearts with normal contractile function. Nevertheless, the presented results have shown a continuously increasing systolic wall thickening, and thus contractile function, from the base to the apex in normal hearts, whereas in cardiomyopathic dilated left ventricles systolic wall thickening was diminished at the midventricular and apical levels. Prior studies in humans and animals (9-13) have also shown a gradient in the extent of systolic wall thickening from basal to apical levels in normal hearts. However, although marked variability in segmental left ventricular wall thickening in patients with dilated cardiomyopathy has been described (28-30), the contractile pattern of the dilated, cardiomyopathic left ventricle along its long axis has not been recognized.

Conclusions. The current study has shown that measurements of left ventricular volumes obtained with cine NMR imaging in a transverse and short-axis imaging plane are nearly identical. Left ventricular mass over a broad range may be accurately determined in a short-axis view. Left ventricular systolic wall thickening can be assessed in normal and cardiomyopathic, dilated hearts. Thus, cine NMR imaging of the heart in a short-axis plane may provide comprehensive evaluation of the geometry and function of the entire left ventricle and quantitative differences in contractile geometry in the abnormal compared with the normal ventricle.

References


