JOURNAL OF CARDIOVASCULAR MAGNETIC RESONANCE®
Vol. 6, No. 4, pp. 845–854, 2004

VENTRICULAR FUNCTION

Accuracy of One- and Two-Dimensional Algorithms with Optimal Image Plane Position for the Estimation of Left Ventricular Mass: A Comparative Study Using Magnetic Resonance Imaging

Theano Papavassiliu, M.D.,[1,*] Harald P. Kühl, M.D.,[1] Willem van Dockum, M.D.,[1] Mark B. M. Hofman, Ph.D.,[2] Olga Bondarenko, M.D.,[1] Aernout M. Beek, M.D.,[1] and Albert C. van Rossum, M.D., Ph.D.[1]

[1]Department of Cardiology, and [2]Department of Clinical Physics and Informatics, VU University Medical Center, Amsterdam, The Netherlands

ABSTRACT

The commonly recommended one-dimensional (1D) and two-dimensional (2D) algorithms for left ventricular (LV) mass calculation are limited by assumptions about ventricular geometry and image plane position. To assess the accuracy of these algorithms after eliminating errors associated with image plane position, LV mass was calculated from high quality cardiovascular magnetic resonance imaging (CMR) data sets using 1D (modified cube formula; MCF) and 2D algorithms [area-length (AL) and truncated ellipsoid (TE) methods], and the summation of slices (SS) method as reference technique in 25 patients with LV aneurysms, 15 patients with hypertrophic cardiomyopathy, and 10 healthy subjects. Each algorithm in each group overestimated LV mass compared to SS ($p < 0.05$ and $p < 0.001$). In each patient group, the smallest bias to the reference method was observed for the TE algorithm ($p < 0.001$ vs. MCF and $p < 0.05$ vs. AL). The LV mass interval encompassing the limits of agreement was 120–220 g for MCF, 100–148 g for AL, and 80–136 g for TE. The interstudy reproducibility of the SS technique for the assessment of LV mass was superior

*Correspondence: Theano Papavassiliu, M.D., First Department of Medicine, University Hospital of Mannheim, Theodor-Kutzer-Ufer 1-3, Mannheim 68167, Germany; Fax: 0049-621-383-3061; E-mail: theano.papavassilliu@med.ma.uni-heidelberg.de.

DOI: 10.1081/JCMR-200036157
1097-6647 (Print); 1532-429X (Online)

compared to the 1D and 2D algorithms. We conclude that despite the use of optimized image plane position 1D and 2D algorithms are inaccurate for calculation of LV mass in ventricles with normal and distorted LV geometry. Thus, 3D imaging techniques, such as CMR, should be preferred when assessing LV mass.

Key Words: Cardiovascular magnetic resonance imaging; Echocardiography; Left ventricular mass; Optimized image planes.

INTRODUCTION

Elevated left ventricular (LV) mass is a powerful and independent prognostic predictor of cardiovascular morbidity and mortality (Casale et al., 1986; Koren et al., 1991; Levy et al., 1990). Therefore, the accurate estimation of LV mass is important for risk stratification and to guide clinical management. Despite its well-known limitations, one-dimensional (1D) M-Mode echocardiography has been used extensively for the calculation of LV mass. The method has been validated anatomically (Devereux and Reichek, 1977; Devereux et al., 1986) and proved to be useful in several studies. However, due to the large variability of the method, these studies required inclusion of large numbers of patients (Casale et al., 1986; Ganau et al., 1992; Levy et al., 1990; Verdecchia et al., 1998). Two-dimensional (2D) algorithms have been shown to be more accurate than 1D algorithms, especially in patients with distorted LV geometry (Reichek et al., 1983). Both methods rely on mathematical models requiring assumptions about the shape of the left ventricle. Moreover, these algorithms depend on the correct position of the imaging planes in 3D space, a condition seldom fulfilled using 1D or 2D echocardiography (King et al., 1992). The value of the algorithms for the estimation of LV mass with optimized positioning of imaging planes has not been assessed.

Cardiovascular magnetic resonance imaging (CMRI) is an established reference standard for the assessment of LV volumes and mass using the summation of slices (SS) method (Caputo et al., 1987; Katz et al., 1988; Lorenz et al., 1999). As a 3D imaging technique, it is independent from geometrical assumptions and is not limited in the position and orientation of the image planes. Additionally, high-quality image data sets are acquired using state-of-the art scanners (Barkhausen et al., 2001).

The aim of this study was to assess the accuracy of geometric assumptions of 1D and 2D algorithms used for the calculation of LV mass after eliminating errors associated with image plane position. For this purpose, LV mass was calculated in 40 patients with severely distorted LV shape and in 10 normal volunteers from high-quality CMR data sets with optimized imaging plane position as recommended by the American Society of Echocardiography (Sahn et al., 1978; Schiller et al., 1989a). The SS method was used as the reference.

MATERIALS AND METHODS

Study Population

The study population consisted of 50 subjects (30 males and 20 females, mean age 55 ± 17 years, range 17–78 years). Ten healthy volunteers (34 ± 7 years) without evidence of cardiovascular disease, normal cardiac dimensions and geometry, and normal systolic function [mean ejection fraction (EF) $64 \pm 6\%$] served as control group. The patient group included 25 patients (64 ± 11 years) with left ventricular aneurysms and severely reduced LV function (mean EF $19 \pm 5\%$), and 15 patients (53 ± 17 years) with hypertrophic obstructive cardiomyopathy (mean EF $69 \pm 4\%$). All subjects were in a stable clinical condition and each subject gave written informed consent prior to participation in the study according to the requirements of the local Ethics Committee.

Image Acquisition

All studies were performed on a 1.5 Tesla whole body imaging system (Magnetom Sonata, Siemens Medical Systems, Erlangen, Germany). A dedicated four-element cardiac phased-array coil was used. Images were acquired during repeated end-expiratory breath holds. Scout images were obtained for planning of the final double-oblique long-axis and short-axis views. Electrocardiogram-gated cine images were then acquired using a segmented steady-state free precession sequence (True-FISP); TE/TR 1.2/3.2 ms, temporal resolution 35 ms, $1.4 \times 1.8 \times 5$ mm^3). Three long-axis views and 7 to 12 short-axis views 1 cm apart covering the whole left ventricle were obtained. Scanning time for the short-axis slices ranged between 10–15 min.

IMAGE ANALYSIS AND DETERMINATION OF VENTRICULAR PARAMETERS

Summation of Slices Method

Images were transferred to a separate workstation (Sun Sparcstation, Sun Microsystems, Mountain View, CA). Analysis was performed using the MASS software package (Medis, Leiden, the Netherlands), as previously reported (Marcus et al., 1999). The cine loops were reviewed, and the end-diastolic and end-systolic frames were identified for each short-axis slice position. End-diastole was defined as the frame showing the largest cavity area and end-systole was defined as the frame revealing the smallest cavity area. Epicardial and endocardial contours were outlined manually on each end-diastolic short-axis frame. The papillary muscles were outlined separately and were included for LV mass measurements. The most basal slice was defined as the slice that at end-diastole and end-systole still showed wall thickness compatible with LV myocardium. At end-systole, this most basal slice could also show a part of the LV outflow tract or the mitral valve leaflets. The most basal slice could differ by one slice position between end-diastole and end-systole. Analysis time averaged 30 min per subject.

For mass determination, the areas subtended by the endocardial and epicardial tracings were determined in each end-diastolic slice and multiplied by slice thickness to yield the myocardial volume. Total myocardial volume was obtained after the summation of data of all individual slices. To obtain LV, mass total myocardial volume at end-diastole was multiplied by 1.05 g/cm^3.

For volume determination, the areas subtended by the endocardial tracings were determined in each end-diastolic and end-systolic slice and multiplied by slice thickness to yield the end-diastolic and end-systolic volumes. Total end-diastolic and end-systolic cavity volumes were obtained after the summation of data of all individual slices. Stroke volume was calculated as the difference between end-systolic and end-diastolic volumes, and the ejection fraction (EF) was calculated as the stroke volume divided by the end-diastolic volume multiplied by 100.

To assess interstudy variability, six healthy volunteers underwent two CMR examinations within 1 week by different operators. The two CMR scans were analysed a minimum 2 weeks apart from each other, with the investigator blinded to the subject's name and the previous results.

One-Dimensional Algorithm

For the estimation of LV mass from 1D measurements, the modified cube formula (MCF) as described by Devereux et al. (1986) was used in accordance with the recommendations of the ASE (Fig. 1). The geometrical model assumes two equal minor axes and a major axis of double the minor axis. Thus, LV mass can be determined exclusively from the minor axis. Left ventricular mass is calculated from the thickness of the anterior septum (IVST) and posterior wall (PWT) and from the left ventricular internal diameter (LVID) measured at end-diastole at the junction of the

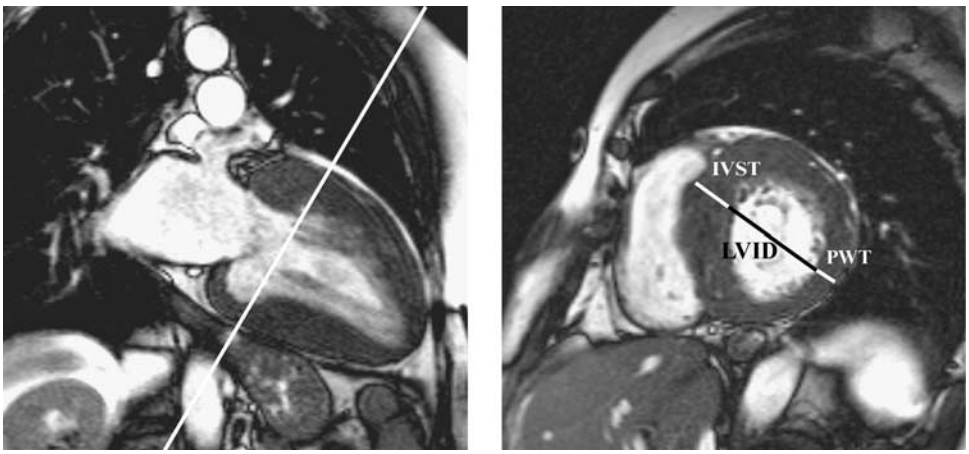

Figure 1. In this short-axis slice, the end-diastolic frame was selected and the LVID, IVST, and PWT were measured.

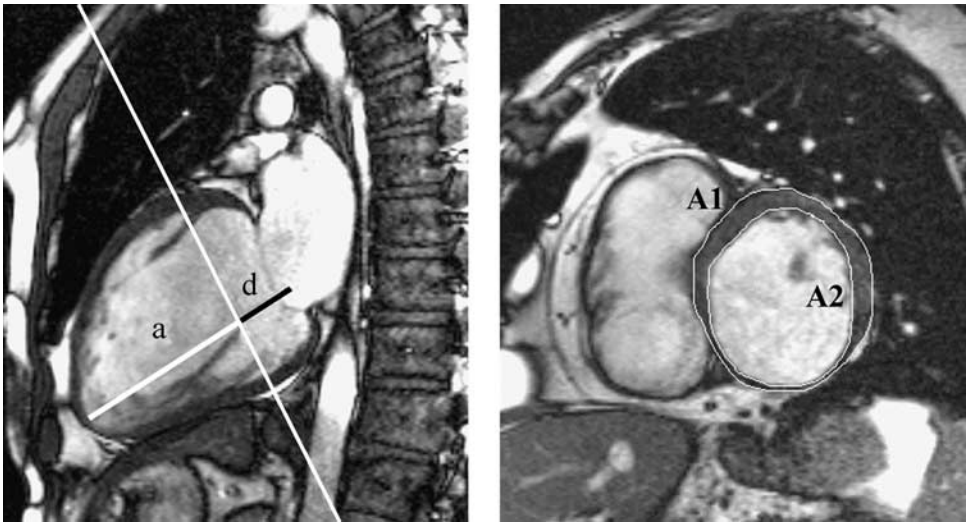

Figure 2. Two-dimensional algorithms show the determination of myocardial cross-sectional area from the papillary muscle tip-level short-axis image.

papillary muscle tips and mitral chordae according to the ASE-corrected equation:

$$\text{LV mass}_{\text{MCF}} = 0.8[1.04[(\text{IVST} + \text{LVID} + \text{PWT})^3 - \text{LVID}^3]] + 0.6 \text{ g}$$

For the determination of the optimal image plane for data analysis in the CMR data set, the cine loops of the long-axis views were reviewed and the location of the papillary muscle tip-chordal junction was identified. The short-axis slice located in closest proximity to this papillary muscle tip-chordal junction was used for subsequent measurements. In this slice, the end-diastolic frame was selected and the LVID, IVST, and PWT were measured as demonstrated in Fig. 1.

Two-Dimensional Algorithms

For the calculation of LV mass using 2D algorithms, the ASE-recommended area-length (AL) and truncated-ellipsoid (TE) formulae were used (Schiller et al., 1989b):

$$\text{LV mass (AL)} = 1.05\{[5/6\ \text{A1}(a + d + t)] - [5/6\ \text{A2}(a + d)]\}$$

$$\text{LV mass (TE)} = 1.05\pi\{(b + t)^2[2/3(a + t) + d - d^3/3(a + t)^2] - b^2[2/3a + d - d^3/3a^2]\}$$

The fundamental step in both algorithms is the determination of myocardial cross-sectional area from

Table 1. Left ventricular parameters measured by CMR for the different patient groups.

Parameter	Controls ($n = 10$)	Aneurysms ($n = 25$)	HCM ($n = 15$)
LV mass (g) by SS	118 ± 18	179 ± 45†	226 ± 57†
LVID (mm)	50.2 ± 6	70.0 ± 13*	50.1 ± 6
IVST (mm)	8.1 ± 2.8	9.7 ± 3.0	14.7 ± 3.9†
EDV (ml)	139 ± 31	332 ± 119†	183 ± 39*
ESV (ml)	51 ± 15	273 ± 107†	56 ± 14
SV (ml)	88 ± 20	62 ± 22*	127 ± 29*
EF (%)	64 ± 6	19 ± 5†	69 ± 4*

Abbreviations: HCM-hypertrophic cardiomyopathy; LV-left ventricular; LVID-left ventricular internal diameter; IVST-interventricular septum thickness; EDV-end-diastolic volume; ESV-endsystolic volume; SV-stroke volume; EF-ejection fraction.

†$p < 0.001$ vs. controls.

*$p < 0.05$ vs. controls.

Table 2. Left ventricular mass (mean ± SD) determined with 1D and 2D algorithms and with the summation of slices method.

	Controls ($n=10$)	Aneurysmatic LV ($n=25$)	HCM ($n=15$)	All subjects ($n=50$)
MCF (g)	165 ± 40*	275 ± 69†	326 ± 68†	268 ± 85†
AL (g)	167 ± 41*	221 ± 54†	325 ± 82†	241 ± 85†
TE (g)	145 ± 35*	194 ± 47	288 ± 78†	212 ± 75†
SS (g)	118 ± 18	179 ± 45	226 ± 57	181 ± 58

Abbreviations: D-dimensional; MCF-modified cube formula; AL-area length algorithm; TE-truncated ellipsoid algorithm; SS-summation of slices algorithm.
*$p < 0.05$.
†$p < 0.001$.

the papillary muscle tip-level short-axis image (Fig. 2). The areas subtended by the epicardial (A1) and endocardial (A2) boundaries are assumed to be a circle, the radius (b) of which can be calculated from the relationship $A2 = \pi b^2$. Mean wall thickness (t) can be approximated from the difference between the two areas. Both algorithms also require the maximum long-axis distance between the mitral annulus and the most apical endocardium for the calculation of LV mass. Thus, two image planes are required to calculate LV mass, which are considered to be orthogonal to each other. In the CMR data sets, the long-axis view with maximal distance from apex to the mid-mitral annulus was selected. The cine loop was reviewed and the location of the papillary muscle tip-chordal junction was identified. This junction was chosen as the location of the minor axis (2b). The placement of the minor axis determined the length of the semimajor axis (a) and the truncated semimajor axis (d), as well as the position of the perpendicular short-axis plane. End-diastolic endocardial and epicardial contours of this short-axis image were manually traced, excluding papillary muscles according to the recommendations of the ASE. Figure 2 is an example of the different MR views selected for LV mass calculation and shows the different measurements needed to calculate LV mass.

Statistics

Data are presented as mean value ± standard deviation. Results for LV mass calculated from the 1D and 2D algorithms were compared with results obtained by SS using linear regression analysis separately for each group. Agreement between the different algorithms and the reference technique was determined according to the method proposed by Bland and Altman (1986). Because of multiple measurements per subject, a repeated measures ANOVA test was performed to assess differences between the four imaging methods for LV mass calculation. A post hoc analysis was added to evaluate interactions between the different imaging modalities. Alpha level adjustment for multiple pair-wise comparisons was applied according to Bonferroni with an alpha error of 5% considered statistically significant. The SPSS 10.0 software package (Chicago, IL) was used for analysis.

The interstudy reproducibility was assessed according to the method described by Bland and Altman.

Table 3. Correlation coefficients, mean absolute differences and 95% confidence limits between 1D and 2D algorithms and the reference technique for LV mass calculation.

	Normals (n = 10)			Anereuysmatic LV (n = 25)			HCM (n = 15)			All subjects (n = 50)		
	r	Mean diff (g)	Limits of agreement (g)	r	Mean diff (g)	Limits of agreement (g)	r	Mean diff (g)	Limits of agreement (g)	r	Mean diff (g)	Limits of agreement (g)
MCF	0.70	46 ± 30	− 14 to 106	0.66	96 ± 52	− 8 to 200	0.62	100 ± 55	− 10 to 210	0.79	87 ± 53	− 19 to 193
AL	0.93	48 ± 25	− 2 to 98	0.74	42 ± 37	− 32 to 82	0.94	99 ± 35	− 29 to 169	0.89	61 ± 42	− 23 to 145
TE	0.90	27 ± 20	− 13 to 67	0.72	15 ± 34	− 53 to 87	0.94	62 ± 28	− 6 to 118	0.89	31 ± 36	− 41 to 103

Abbreviations: LV-left ventricle; HCM-hypertrophic cardiomyopathy; r-correlation-coefficient; MCF-modified cube formula; AL-area length algorithm; TE-truncated ellipsoid algorithm.

The mean bias between two repeated studies, the limits of agreement, and the coefficient of variability (equal to the standard deviation of the difference between the two measurements over the mean of the two measurements, expressed as a percentage) were calculated.

RESULTS

Table 1 summarizes results for LV mass, LVID, IVST, LV volumes, and EF measured separately for each patient group and for the control group. The ratio of long-axis length to short-axis diameter was 1.9 ± 0.3 in normal ventricles, 1.9 ± 0.2 in ventricles with hypertrophic obstructive cardiomyopathy (p = ns vs. normals), and 1.6 ± 0.4 in ventricles with aneurysms ($p = 0.025$ vs. normals).

LV Mass

Table 2 lists results of mean LV mass for the different techniques and patient groups. Compared to the reference technique, the 1D and 2D algorithms overestimated LV mass in each group and in the study population as a whole. Table 3 gives the correlation coefficients, mean differences, and limits of agreement for the 1D and 2D algorithms compared to SS, according to the different groups investigated. Figure 3 shows Bland-Altman plots of individual differences between the 1D and 2D algorithms and the reference method.

For the 1D algorithm, the highest correlation coefficient and the lowest variability was observed for the normal left ventricles, whereas correlation was lower for the aneurysmatic and hypertrophic left ventricles. Overestimation and variability, expressed as the SD of the differences, was similar for aneurysmatic ventricles and hypertrophic ventricles. The LV mass interval encompassing the limits of agreement averaged 120 g for normal hearts, 208 g for aneurysmatic ventricles, and 220 g for hypertrophic hearts.

For the 2D algorithms, correlation coefficients were similar for the normal and hypertrophic ventricles and lower for the aneurysmatic hearts. Overestimation was similar for the normal and aneurysmatic ventricles, but was more pronounced for the hypertrophic ventricles. The LV mass interval encompassing the limits of agreement averaged 80 and 100 g for normal hearts, 136 and 148 g for aneurysmatic ventricles, and 112 and 140 g for hypertrophic hearts for the TE and AL algorithms, respectively.

Interstudy Variability

The interstudy variability of SS measurements was lower than the variability of 1D and 2D measurements. Table 4 gives the coefficients of variability, mean differences, and limits of agreement for the SS method and the 1D and 2D algorithms. The LV mass interval encompassing the limits of agreement was 24 g for

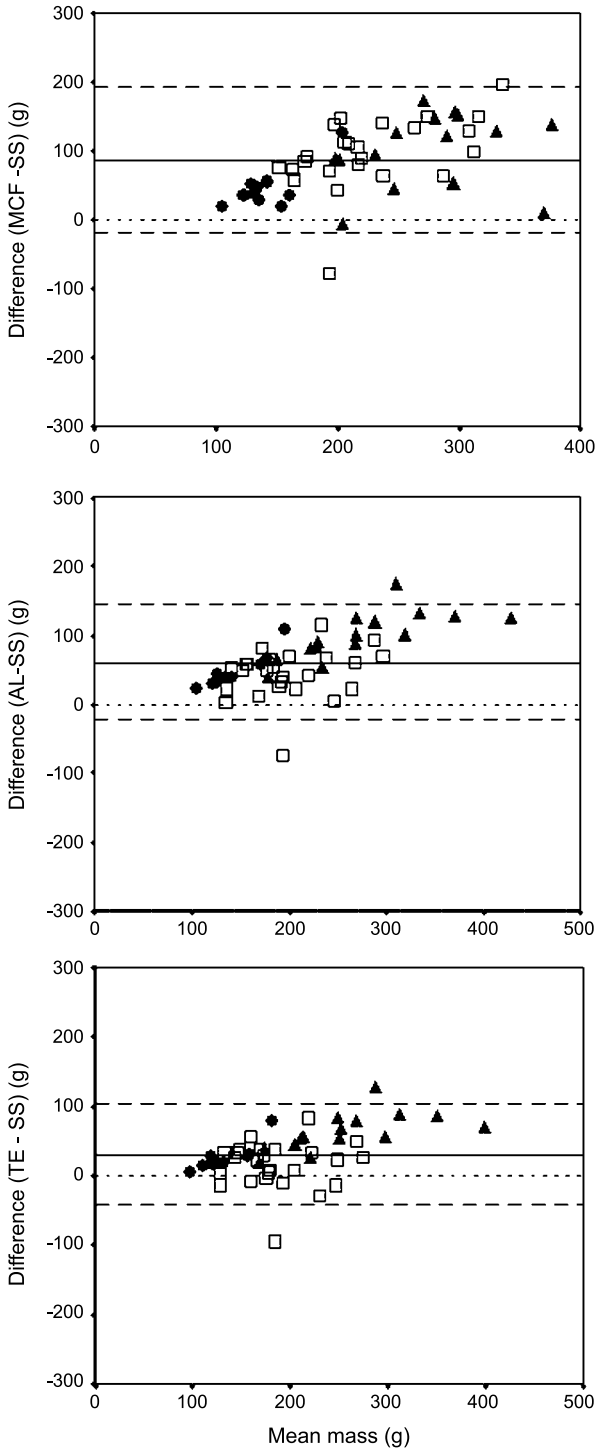

Figure 3. Bland-Altman plots of individual differences between the 1D and 2D algorithms and the reference method.

Table 4. Interstudy reproducibility data (n = 6).

	SS	AL	TE	MCF
LV mass (g)				
Mean difference ± SD (g)	2 ± 6	− 5 ± 15	− 5 ± 13	9 ± 24
Limits of agreement (g)	− 10 to 14	− 35 to 25	− 31 to 21	− 39 to 57
Coefficient of variability	4%	8%	8%	17%

Abbreviations: LV mass-left ventricular mass; Mean difference-mean difference between the 2 measurements; SD-standard deviation; SS-summation of slices algorithm; AL-area length algorithm; TE-truncated ellipsoid algorithm; MCF-modified cube formula.

measurements by the SS method, 96 g for the 1D algorithm, 60 g for AL, and 52 g for the TE algorithm.

DISCUSSION

Since the introduction of echocardiography, the accurate determination of LV mass has received great attention and various methods based on 1D and 2D algorithms have been introduced (Devereux and Reichek, 1977; Reichek, 1983; Schiller et al., 1983). The main limitations of these algorithms are 1) simplifying assumptions about the geometry of the left ventricle and 2) image plane positioning errors. As previously demonstrated, the correct position of the image planes is a condition that is neither verified during echocardiographic scanning nor commonly attained (King et al., 1992). However, the relative importance of optimizing image planes for the calculation of LV mass is not known. The results of this study demonstrate that despite the use of optimal image planes, 1D and 2D algorithms used for the determination of LV mass are inaccurate compared with the reference method.

Left ventricular mass by the 1D technique was consistently larger compared to the reference method in all patient groups. The highest correlation coefficient and the lowest variability were observed in the group of normal controls. This finding is not unexpected, because the shape of these ventricles fulfilled the geometric assumptions of the model. In contrast, a poor correlation and broad limits of agreement were found in the aneurysmatic ventricles where the geometric assumptions were not met. Similar results were also observed in the hypertrophic cardiomyopathy patients. Overestimation and measurement inaccuracy may be primarily related to the asymmetric distribution of LV hypertrophy in this patient group.

Overestimation of LV mass by M-mode compared with CMR has been reported previously in patients with hypertensive hypertrophy (Bottini et al., 1995; Missouris et al., 1996), transplant recipients (Bellenger et al., 2000), in patients with abnormal left ventricular shape (Gopal et al., 1997), and, more recently, also in normal subjects from the Framingham population (Salton et al., 2002). Thus, several studies indicate that, compared to 3D methods, the 1D algorithm yields larger LV mass values.

Similarly, both 2D techniques overestimated LV mass relative to the reference method in all groups. However, in the ischemic cardiomyopathy patients, mean LV mass by the TE method was not different from mean LV mass assessed by the reference method. Less overestimation by the 2D method compared with the 1D method has also been reported in two studies that compared these methods with CMR in patients with normal and abnormal left ventricular shape (Gopal et al., 1997; Pluim et al., 1997). As expected, high correlation coefficients were found between AL, TE, and the reference method in the normal ventricles. High correlation coefficients were also found in the hypertrophic ventricles, demonstrating that the global shape of these ventricles was not significantly different from the geometrical model underlying the algorithm. The increased measurement variability may be explained by the nonuniform distribution of mass that is ignored by the 2D algorithm. The lowest correlation coefficients and broadest limits of agreement for both methods were observed in the group of aneurysmatic left ventricles. Similar to the results of the present study, Gopal et al. reported overestimation of LV mass and large measurement variability by 2D echocardiography compared with CMR in patients with abnormal left ventricles.

Recently, Myerson et al. (2002) examined the MCF and AL formulas by applying them to CMR and compared the results to LV mass calculated by the SS method in 212 healthy subjects. Consistent with the findings of the present study, LV mass calculated by the 1D and 2D formulas resulted in significant variation from the measurements by the SS method. However, in conflict to our study and to several

previous reports (Bottini et al., 1995; Gopal et al., 1997; Missouris et al., 1996; Salton et al., 2002), these authors reported larger mass values with the CMR technique compared with 1D and 2D algorithms. This finding may be partially explained by important differences in the CMR technique that was applied in the Meyerson study (Myerson et al., 2002): 1) use of a 0.5 T scanner, which results in lower signal-to-noise ratio, 2) lower spatial resolution of the imaging sequence used 3) increased partial volume effect associated with use of a slices thickness of 10 mm, and 4) differences between conventional gradient-echo and fast imaging with steady-state precession sequence used in our study (Alfakih et al., 2003; Moon et al., 2002). These factors may have affected mass calculation with the SS method as well as with the 1D and 2D techniques. Interestingly, the same group reported overestimation of LV mass by the 1D algorithm when using a 1.5 T CMR scanner and echocardiography as imaging modalities (Bellenger et al., 2000).

The present study confirms the excellent interstudy reproducibility of CMR for the assessment of LV mass (Grothues et al., 2002). More importantly, however, it demonstrates superior reproducibility of the SS method over the 1D and 2D algorithms, even after eliminating errors associated with image plane position.

Limitations

We used a steady-state free precession sequence for the calculation of LV mass, which has been reported to yield lower LV mass values compared with conventional gradient-echo imaging techniques (Alfakih et al., 2003; Grothues et al., 2002). However, in a recent in vivo animal experiment, the steady-state free precession sequence has been validated for LV mass calculation with excellent agreement compared with true LV mass (Fieno et al., 2002). The variable inclusion of trabeculae and papillary muscles, when contiguous with the left ventricular free wall, may be a source of error associated with the SS method, which may explain some of the variability of the results. Moreover, the high contrast between myocardium and blood and the excellent spatial resolution of the imaging sequence allows for visualization of great morphological detail, which may complicate manual contour tracing. The patient population was selected for severely distorted ventricles that represent the extremes of the spectrum of the diseased heart. A more realistic patient population might have resulted in more favourable comparison between the methods. Moreover, the population of normal subjects was small and younger compared to the patient population, including a narrow range of mass values, which might explain the moderate correlation coefficient found in this study group.

CONCLUSION

Despite the use of optimal image planes, 1D and 2D algorithms overestimate LV mass and reveal broad limits of agreement compared with CMR in patients with normal as well as distorted LV geometry. Given optimal image quality and perfect plane orientation, the TE method results in least bias compared with the SS method and may be the preferred technique for the assessment of LV mass using conventional echocardiography when 3D imaging methods are not available.

ABBREVIATIONS

D	dimensional
LV	left ventricular
CMR	cardiovascular magnetic resonance
MCF	modified cube formula algorithm
AL	area length algorithm
TE	truncated ellipsoid algorithm
SS	summation of slices algorithm
IVST	interventricular septum thickness
LVID	left ventricular internal diameter
PWT	posterior wall thickness
EF	ejection fraction

ACKNOWLEDGMENTS

This work was supported by grants 99.203 and 2001.158 from the Dutch Heart Foundation. Dr. Papavassiliu was supported by a grant from the Medical Faculty of the University of Mannheim, Germany. Dr. Kühl was supported in part by grants from the Medical Faculty of the Rheinisch-Wesfälische Technische Hochschule, Aachen, and the Grimmke-Stiftung, Düsseldorf, Germany.

REFERENCES

Alfakih, K., Plein, S., Thiele, H., Jones, T., Ringway, J. P., Sivananthan, M. U. (2003). Normal human left and right ventricular dimensions for MRI as assessed by turbo gradient echo and steady-state free precession imaging sequences. *J. Magn. Reson. Imaging* 17:323–329.

Barkhausen, J., Ruehm, S. G., Goyen, M., Buck, T., Laub, G., Debatin, J. F. (2001). MR evaluation of ventricular function: true fast imaging with steady-state precession versus fast low-angle shot cine MR imaging: feasibility study. *Radiology* 219: 264–269.

Bellenger, N. G., Marcus, N. J., Davies, C., Yacoub, M., Banner, N. R., Pennell, D. J. (2000). Left ventricular function and mass after orthotopic heart transplantation: a comparison of cardiovascular magnetic resonance with echocardiography. *J. Heart Lung Transplant.* 19:444–452.

Bland, J. M., Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1:307–310.

Bottini, P. B., Carr, A. A., Prisant, L. M., Flickinger, F. W., Allison, J. D., Gottdiener, J. S. (1995). Magnetic resonance imaging compared to echocardiography to assess left ventricular mass in the hypertensive patient. *Am. J. Hypertens.* 8:221–228.

Caputo, G. R., Tscholakoff, D., Sechtem, U., Higgins, C. B. (1987). Measurement of canine left ventricular mass by using MR imaging. *Am. J. Roentgenol.* 148:33–38.

Casale, P. N., Devereux, R. B., Milner, M., et al. (1986). Value of echocardiographic measurement of left ventricular mass in predicting cardiovascular morbid events in hypertensive men. *Ann. Intern. Med.* 105:173–178.

Devereux, R. B., Reichek, N. (1977). Echocardiographic determination of left ventricular mass in man. Anatomic validation of the method. *Circulation* 55(4):613–618.

Devereux, R. B., Alonso, D. R., Lutas, E. M., et al. (1986). Echocardiographic assessment of left ventricular hypertrophy: comparison to necropsy findings. *Am. J. Cardiol.* 57:450–458.

Fieno, D. S., Jaffe, W. C., Simonetti, O. P., Judd, R. M., Finn, J. P. (2002). TrueFISP: assessment of accuracy for measurement of left ventricular mass in an animal model. *J. Cardiovasc. Magn. Reson.* 15:526–531.

Ganau, A., Devereux, R. B., Roman, M. J., et al. (1992). Patterns of left ventricular hypertrophy and geometric remodeling in essential hypertension. *J. Am. Coll. Cardiol.* 19:1550–1558.

Gopal, A. S., Schnellbaecher, M. J., Shen, Z., Boxt, L. M., Katz, J., King, D. L. (1997). Freehand three-dimensional echocardiography for determination of left ventricular volume and mass in patients with abnormal ventricles: comparison with magnetic resonance imaging. *J. Am. Soc. Echocardiogr.* 10(8):853–861.

Grothues, F., Smith, G. C., Moon, J. C., Bellenger, N. G., Collins, P., Klein, H. U., Pennell, D. J. (2002). Comparison of interstudy reproducibility of cardiovascular magnetic resonance with two-dimensional echocardiography in normal subjects and in patients with heart failure or left ventricular hypertrophy. *Am. J. Cardiol.* 90(1):29–34.

Katz, J., Milliken, M. C., Stray-Gundersen, J., et al. (1988). Estimation of human myocardial mass with MR imaging. *Radiology* 169:495–498.

King, D. L., Harrison, M. R., King, D. L. Jr., Gopal, A. S., Kwan, O. L., DeMaria, A. N. (1992). Ultrasound beam orientation during standard two-dimensional imaging: assessment by three-dimensional echocardiography. *J. Am. Soc. Echocardiogr.* 5:569–576.

Koren, M. J., Devereux, R. B., Casale, P. N., Savage, D. D., Laragh, J. H. (1991). Relation of left ventricular mass and geometry to morbidity and mortality in uncomplicated essential hypertension. *Ann. Intern. Med.* 114:345–352.

Levy, D., Garrison, R. J., Savage, D. D., Kannel, W. B., Castelli, W. P. (1990). Prognostic implications of echocardiographically determined left ventricular mass in the Framingham Heart Study. *N. Engl. J. Med.* 322:1561–1566.

Lorenz, C. H., Walker, E. S., Morgan, V. L., Klein, S. S., Graham, T. P. Jr. (1999). Normal human right and left ventricular mass, systolic function, and gender differences by cine magnetic resonance imaging. *J. Cardiovasc. Magn. Reson.* 1:7–21.

Marcus, J. T., DeWaal, L. K., Gotte, M. J., van der Geest, R. J., Heethaar, R. M., Van Rossum, A. C. (1999). MRI-derived left ventricular function parameters and mass in healthy young adults: relation with gender and body size. *Int. J. Card. Imaging* 15:411–419.

Missouris, C. G., Forbat, S. M., Singer, D. R., Markandu, N. D., Underwood, R., MacGregor, G. A. (1996). Echocardiography overestimates left ventricular mass: a comparative study with magnetic resonance imaging in patients with hypertension. *J. Hypertens.* 14:1005–1010.

Moon, J. C. C., Lorenz, C. H., Francis, J. M., et al. (2002). Breath-hold FLASH and FISP cardiovascular MR imaging: left ventricular volume differences and reproducibility. *Radiology* 223:789–797.

Myerson, S. G., Montgomery, H. E., World, M. J., Pennell, D. J. (2002). Left ventricular mass. Reliability of M-mode and 2-dimensional echocardiographic formulas. *Hypertension* 40:673–678.

Pluim, B. M., Beyerbacht, H. P., Chin, J. C., et al. (1997). Comparison of echocardiography with magnetic resonance imaging in the assessment of the athlete's heart. *Eur. Heart J.* 18:1505–1513.

Reichek, N. (1983). Echocardiographic assessment of left ventricular structure and function in hypertension. Methodology. *Am. J. Med.* 75:19–25.

Reichek, N., Helak, J., Plappert, T., Sutton, M. S., Weber, K. T. (1983). Anatomic validation of left ventricular mass estimates from clinical two-dimensional echocardiography: initial results. *Circulation* 67:348–352.

Sahn, D., DeMaria, A., Kisslo, J., Weyman, A. (1978). The committee on M-mode standardization of the American Society of Echocardiography. Recommendations regarding quantitation in M-mode echocardiography: results of a survey of echocardiograpic measurements. *Circulation* 58:1072–1083.

Salton, C. J., Chuang, M. L., O'Donnell, C. J., et al. (2002). Gender differences and normal left ventricular anatomy in an adult population free of hypertension. A cardiovascular magnetic resonance study of the Framingham Heart Study Offspring cohort. *J. Am. Coll. Cardiol.* 39:1055–1060.

Schiller, N. B., Skiôldebrand, C. G., Schiller, E. J., et al. (1983). Canine left ventricular mass estimation by two-dimensional echocardiography. *Circulation* 68:210–216.

Schiller, N. B., Shah, P. M., Crawford, M., et al. (1989a). Recommendations for quantitation of the left ventricle by two-dimensional echocardiography. American Society of Echocardiography Committee on Standards, Subcommittee on Quantitation of Two-Dimensional Echocardiograms. *J. Am. Soc. Echocardiogr.* 2:358–367.

Schiller, N. B., Shah, P. M., Crawford, M., et al. (1989b). Recommendations for quantitation of the left ventricle by two-dimensional echocardiography. American Society of Echocardiography Committee on Standards, Subcommittee on Quantitation of Two-Dimensional Echocardiograms. *J. Am. Soc. Echocardiogr.* 2:358–367.

Verdecchia, P., Schillaci, G., Borgioni, C., et al. (1998). Prognostic significance of serial changes in left ventricular mass in essential hypertension. *Circulation* 97:48–54.

Submitted December 4, 2003
Accepted May 5, 2004