Research Paper ■

A Simple Assessment of Left Ventricular Function and Mass with Cine MRI

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Abstract. The purpose of the study was to evaluate the reproducibility of a proposed modified assessment method of end-diastolic volume (EDV), end-systolic volume (ESV), ejection fraction (EF) and mass of the left ventricle (LV). Cine MRI was performed in ten healthy volunteers and eight patients with heart disease presenting focal or global thinning of the LV wall and chamber dilatation. In LV, EDV, ESV, EF and LV mass were determined from the horizontal long axis slice by Simpson's disk method. The results were compared with the values computed from short-axis slices by Simpson's rule. Inter-observer and intra-observer reproducibility of Simpson's disk method in assessing LV volumes were 5.06% and 4.03% in percent variability, respectively. The agreement between Simpson's disk method and Simpson's rule, expressed in standard deviation of the mean bias, was acceptable regarding LV for EDV, ESV, EF and LV mass in the healthy volunteers as well as in the patients. Simpson's disk method may therefore serve as an alternative to assess LV for EDV, ESV, EF, and LV mass if the LV maintains its symmetry, and is clinically useful in patients who cannot tolerate long scan time.

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Introduction

Global function and mass of the left ventricle (LV) are important indicators of stratification, treatment planning and prognosis for a patient with cardiac disease. There exist various imaging modalities and analysis methods to assess LV function and mass. MRI has been recognized a modality of choice because it is non-invasive, free of ionizing radiation, and has excellent image quality, including superior temporal and spatial resolution, and high image contrast between the myocardium and blood. Moreover, MRI provides tomographic images of the heart, allowing determination of LV volumes with Simpson's rule. Typically multiple parallel short-axis slices are acquired encompassing the whole LV. The volumes are determined by summing up areas of the LV cavity at each level multiplied by the slice thickness. Simpson's rule determines LV volumes from three-dimensional data of the LV cavity. The assessment is considered accurate because no geometric assumption is involved. To date, using cardiac MRI and Simpson's rule has become a standard method for clinical assessment of LV function and mass.[1]

The major disadvantage of MRI assessment with Simpson's rule is long scan time. This method requires ECG-gated cine MRI in multiple short-axis slices, steady state free precession (SSFP) sequences with successful intermittent breath holds but intolerable to cardiac patients who are critically ill. The method to assess LV function and mass from a single cine acquisition is still desirable with short scan time in clinical settings. To acquire fewer slices and assuming various geometric shapes to approximate the LV cavity suffers with errors because of mismatch between global shape of the LV cavity and simple shape of geometry. Biplane Simpson's disk method seems more accurate than other methods in assessing LV volumes.[2] A Simpson's disk method was proposed to assess LV volumes with a single cine MRI. The method assumed that the shape of the LV cavity at each short-axis level approximates a disk. Based on this assumption, a series of cine MRI was

acquired in a horizontal long-axis view. The LV volumes were determined by summing up a stack of disks along the LV long axis. The purpose of this paper was to compare the proposed Simpson's disk method with standard Simpson's rule in assessing LV function and mass.

Materials and methods

Subjects

Ten healthy subjects were enrolled in the study. All subjects completed informed consent before MRI examination. The study was performed under the approval of the Institutional Review Board of the hospital.

Imaging techniques

A study was performed on a 1.5 Tesla MRI system (GE Signa) with a four-channel phase array receiver coil. Procedures of prescribing a horizontal long-axis view and short-axis views were described as follows. A transverse slice through the left and right ventricles was obtained. A vertical long-axis slice paralleling the interventricular septum was prescribed from the transverse slice. The horizontal long-axis view (or four-chamber view) was determined by prescribing a slice plane perpendicular to the vertical long-axis slice, and the line of intersection coincided with the line between mitral orifice and cardiac apex. Short-axis views were then determined with the slice planes perpendicular to the horizontal long-axis view and to the LV long axis shown in this view. Cine MRI was acquired in multiple short-axis views covering the whole LV and in a single horizontal long-axis view.

We used prospective electrocardiographic R-wave trigger to synchronize MRI data acquisition. The pulse sequence used a non breath-hold two-dimensional (2D) gradient echo technique with TR/TE/flip angles = 30 ms/7 ms/30°. Short-axis slices were prescribed from cardiac base to apex with slice thickness/gap = 10 mm/0 mm. To avoid

cross talks between adjacent excitation pulses, two slice levels separated by a half range of the coverage were scanned in the same acquisition. Nine to eleven short-axis slices were obtained depending on the cardiac size. Setting temporal resolution at 30 ms, the total number of cardiac phases was determined as 90% of R-R interval divided by 30 ms. In-plane resolution of 1.2 mm was obtained with the field-of-view (FOV) of 30 cm and a matrix size of 128×256 interpolated to 256×256. To reduce respiratory motion artifacts we used two number of excitation (NEX). The resulting images showed clear distinction between LV cavity and endocardial border. Blurring of the border was observed at the most apical slices due to partial volume effect. The scan time was RR interval $\times$ 128 (number of phase encoding) $\times$ 2 (NEX) $\times$ 5 (five acquisitions for ten levels), approximately 21 minutes if RR interval = 1 sec. Heart rate was recorded at the beginning, middle and end of the examination.

Image analysis

To define endocardial boundary of the LV in short-axis views, we used an in-house semi-automated edge detection method based on a gray-level auto-contouring algorithm provided by MATLAB 5.2 (Mathworks, Inc., Natick, MA, USA). Once the coordinates of the points on the boundaries were determined, the area enclosed by the boundary was computed. LV volumes were then determined by Simpson's rule:

$$LV \text{ volume} = \Sigma_{i=1..n} A_i\, t \qquad (1)$$

where n is the total number of slices, A_i is the area of the LV cavity at the i-th level, and t is the slice thickness. From the time course of LV volumes, we identified the volumes at end diastole (EDV), end systolic (ESV) and calculated the ejection fraction (EF). We included slices at cardiac base containing the mitral valves. If the short-axis plane showed the left atrium and left ventricle, we identified the LV cavity enclosed by the ventricular wall and mitral annulus, and traced the endocardial border manually. The number of

slices at end diastole was one to two slices more than that at end systole.

To determine the LV mass, we used the same edge-detection algorithm to define the endocardial and epicardial boundaries at end diastole. The volume of the LV wall was computed by subtracting the volume enclosed by the endocardial boundary from the volume enclosed by the epicardial boundary. We obtained the LV mass by multiplying the wall volume with the density of the myocardium, assuming 1.05

The LV volumes in the horizontal long-axis cine MRI were determined by manually tracing the borders of the endocardium and epicardium. To apply Simpson's disk method, The LV long axis was defined with a line connecting mitral orifice and cardiac apex in the horizontal long-axis view. Multiple parallel segments were produced along the LV long axis with equal increment (Figure 1). These segments were perpendicular to the LV long axis and were bounded by the septum and lateral wall. The lengths of the segments were taken as the diameters of the disks of the same levels. Knowing the diameters of individual disks and the increment, LV volumes were determined by summing up the volumes of these disks:

$$LV \text{ volume} = \Sigma_{i=1..m} \pi\, a\, d_j^2 / 4 \qquad (2)$$

where m is the total number of disks along the LV long axis, d_j is the diameter of the disk at the j-th level, and a is the distance of increment. As described above, we determined the EDV, ESV, EF and LV mass from the measured volumes. Papillary muscles were excluded from the myocardium in both Simpson's rule and Simpson's disk method.
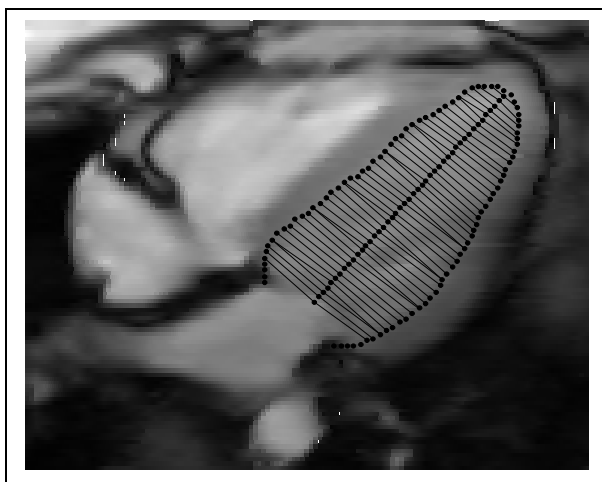
Figure 1 Simpson's disk method using a single horizontal long-axis slice by 1.5 T MRI.

Inter-observer and intra-observer reproducibility

To evaluate the reproducibility of the Simpson's rule and Simpson's disk method, we evaluated the variability of individual methods between two observers, and between two analyses by the same observer. Inter-observer variability was studied by comparing pairs of results analyzed by two observers. Intra-observer variability was studied by comparing pairs of results from the repeated analyses by the same observer two months apart.

Statistical analysis

Reproducibility of each method was quantified in terms of the mean difference between paired measurements, SD of the mean differences and percent variability. Bland-Altman analysis[3,4] was used to evaluate the agreement of LV volumes between the Simpson's disk method and Simpson's rule expressed in terms of the mean bias, upper and lower limits of agreement (mean bias±2SD), and 95% confidence interval of the mean bias in the assessment of LV EDV, ESV, EF and LV mass. Data analysis was performed with MATLAB 5.2 (Mathworks, Inc., Natick, MA, USA) software.

Patient study

To test the feasibility of Simpson's disk method in disease heart, we studied eight patients who presented with focal or global thinning of the LV wall and chamber dilatation. Cine MRI was performed in a 1.5 T scanner (GE Signa) using balanced SSFP (TrueFISP;
TR/TE/flip angle = 22ms/1.8ms/60º). Multiple short-axis slices and one horizontal long-axis slice were obtained at the same spatial and temporal resolution as described above. To demonstrate the LV wall abnormality, delayed enhancement study was performed using inversion-recovery prepared segmented turbo FLASH sequences
(TR/TE/flip angle = 750 ms/4.38ms/10º;
TI = null point of the myocardial signal; 16 segments per acquisition). Data analysis was performed as described above.

Results

Both Simpson's disk method and Simpson's rule showed high intra-observer and inter-observer reproducibility in assessing LV volumes (Table 1). Intra-observer and inter-observer reproducibility in Simpson's disk method were 4.03% and 5.06% in percent variability, respectively, and those in Simpson's rule were 3.02% and 8.49%, respectively.

Table 1 Reproducibility of left ventricular volumes in Simpson's disk method and Simpson's rule.

| Type of variability, Method	SD of mean difference (ml)	Mean difference (ml)	% variability
Intra-observer, Simpson's disk	2.8	0.1	4.03
Inter-observer, Simpson's disk	4.1	-0.7	5.06
Intra-observer, Simpson's rule	1.7	0.4	3.02
Intrer-observer, Simpson's rule	5.2	1.7	8.49
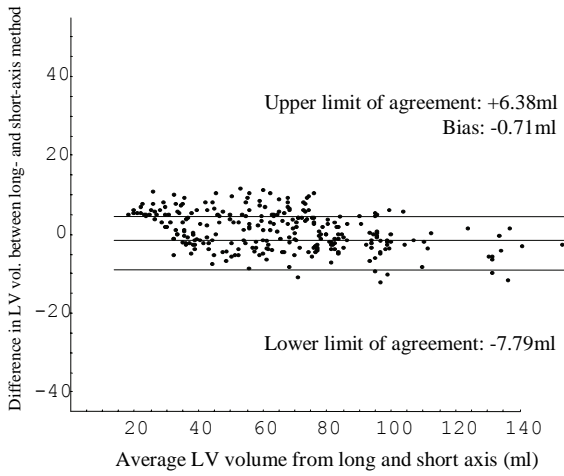
Figure 2 Bland-Altman plot showing agreement between Simpson's disk method and Simpson's rule in the evaluation of LV volumes during cardiac cycle in ten healthy volunteers.

Table 2 Demographic characteristics and normalized left ventricular functional parameters.

Variable (Mean ± SD)	Healthy volunteers (N=10)	Patients with heart disease (N=8)
Age (years)	31.5 ± 10.3	61.6 ± 9.9
Height (cm)	164.0 ± 9.0	167.0 ± 4.7
Weight (kg)	64.0 ± 12.3	64.0 ± 7.9
BSA (m2)	1.97 ± 0.20	1.72 ± 0.13
HR (beats/min)	70 ± 8.0	79 ± 10
EDVI (ml/m2)	45.4 ± 9.8	152.3 ± 67.2
ESVI (ml/m2)	12.4 ± 3.7	117.4 ± 62.7
EF (%)	73.4 ± 2.4	24.1 ± 12.1
Mass (g/m2)	44.4 ± 9.5	103.1 ± 31.3

Abbreviations: BSA=body surface area; HR=heart rate; EDVI=end diastolic volume index; ESVI=end systolic volume index; EF=ejection fraction.
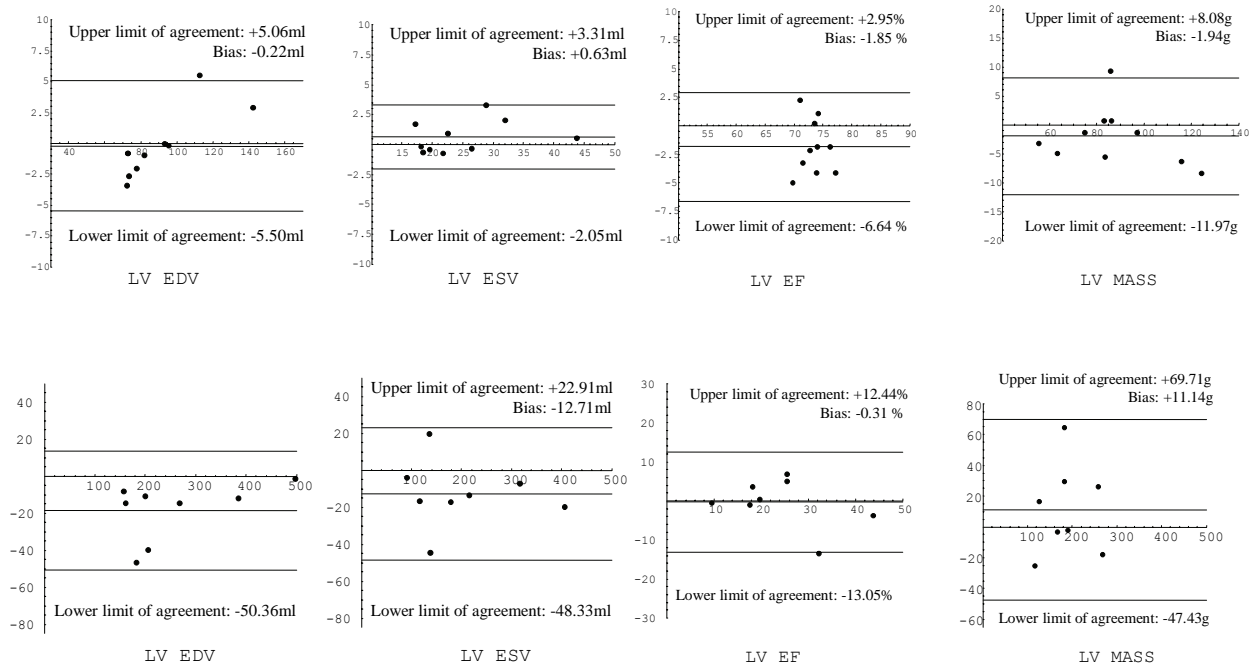
Figure 3 Bland-Altman plots showing agreement between Simpson's disk method and Simpson's rule in the evaluation of in the evaluation of LV EDV, ESV, EF, and LV mass in ten healthy volunteers (top) and eight patients (bottom).

Patient 1　　Patient 2　　Patient 3　　Patient 4

Patient 5　　Patient 6　　Patient 7　　Patient 8
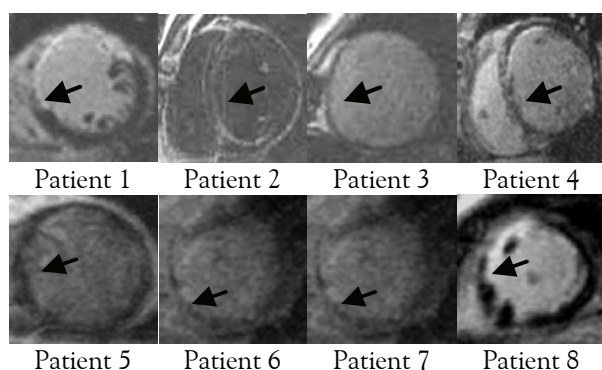
Figure 4 Viability study of eight patients with heart disease by 1.5 T MRI using Cine MRI showing transventricular compartments (notice the regions with signal loss in patient 8).

The agreement between Simpson's rule and Simpson's disk method in the evaluation of LV volumes during cardiac cycles is shown in Figure 2. The mean bias (SD) was -0.71 ml (3.54 ml), 95% confidence interval of the mean bias being [-1.13,-0.28 ml], and the upper/lower limit of agreement being 6.38 ml/-7.79 ml.

Demographic data of healthy volunteers including LV function and mass are summarized in Table 2. Bland-Altman plots of the agreement between Simpson's rule and Simpson's disk method are shown in the top four graphs in Figure 3. The mean bias (SD) between the two methods was -0.22 ml (2.64 ml) for LV EDV, +0.63 ml (1.34 ml) for ESV, -1.85% (2.40%) for EF, and -1.94 g (5.01 g) for LV mass.

Demographic data of the patients including LV function and mass are also summarized in Table 2. Clinical diagnosis and MRI findings of LV wall abnormality and selected images of viability study for each patient are shown in Figure 4. Four patients (patient 1, 2, 4 and 8) with previous history of acute myocardial infarction showed focal hyperenhancement in delayed enhancement study, three patients (patient 5, 6 and 7) with chronic coronary artery disease and one patient (patient 3) with dilated cardiomyopathy did not show hyperenhancement.

Bland-Altman plots of the agreement between Simpson's rule and Simpson's disk method for the patients are shown in the bottom four graphs in Figure 3. The mean bias (SD) between the two methods was -18.30ml (16.01 ml) for LV EDV, -12.71ml (17.81 ml) for ESV, -0.31% (6.37%) for EF, and +11.14g (29.28 g) for LV mass.

Discussion

In the study, we evaluated the reproducibility of Simpson's disk method, and the agreement between this method and Simpson's rule in assessing LV function and mass.

The inter-observer reproducibility of Simpson's rule in our study (8.49%) is comparable with those of other methods reported previously.[5] The percent variability was 4.0% for EDV and 8.6% for ESV in conventional non breath-hold cine MRI; 4.0% for EDV and 8.0% for ESV in breath-hold cine MRI; 6.1% for EDV and 7.8% for ESV in turbo gradient echo; and 2.8% for EDV and 5.5% for ESV in balanced SSFP sequence. In this study, we found slightly better inter-observer reproducibility with Simpson's disk method than with Simpson's rule (5.06% vs. 8.49%).

In healthy volunteers, the agreement between Simpson's disk method and Simpson's rule in assessing LV EDV, ESV, EF, and LV mass revealed small mean bias and narrow SD's of the mean bias. This study in normal heart LV volume and mass by Simpson's disk method suggests that the assumption of disk configuration at each level of short-axis view is valid. Simpson's disk method approximates the shape of LV cavity in piecemeal fashion, reducing the possibility of large error. Single plane in a horizontal long-axis view is reliable to approximate disk diameter.

The agreement between Simpson's disk method and Simpson's rule in assessing LV EF was -0.31% in terms of mean bias and 6.37% in terms of SD of the mean bias. The agreement in LV EDV and ESV in patients showed 16.01 ml and 17.81 ml in

terms of SD of the mean bias, respectively. Large variability in patients may be the consequence of large EDV and ESV (Table 2). The SD of the difference in EDV was 25 ml in patients with global dysfunction and 18 ml in those with regional dysfunction, respectively. For ESV, the SD's were 25 ml and 10 ml, respectively. If the difference between two measurements is normalized by the mean of the two measurements for individual patients, we obtain 6.0% for EDV and 8.7% for ESV, respectively. Therefore, the reliability of Simpson's disk method in assessing LV EDV and ESV in patients is acceptable. As for the agreement of LV mass in patients, the mean bias (SD) was +11.14 gm (29.28 gm), thus apparently larger than that of healthy volunteers. Nevertheless, the reliability of Simpson's disk method in assessing LV mass is also acceptable.

In this study, conventional gradient echo sequence and balanced SSFP sequence both have inherently different contrast mechanisms to define border. During late systolic phase, the contrast between the myocardium and blood around the apex became indistinguishable because blood flow was slow. To determine endocardial contour in this phase, one often needs to play cine loops back and forth to interpolate the contour location. Although error may still exist, we consider it insignificant because the apical volume is small relative to the total LV volume. Comparing with gradient echo sequences, balanced SSFP sequences provide better contrast between the myocardium and blood. The images obtained from balanced SSFP can reveal fine trabeculae, since greater thickness of trabeculae tends to be excluded from the myocardium in border definition. This subsequently leads to systematic difference. Further study on the definition of the border is required to achieve agreement between the balanced SSFP sequences and the conventional gradient echo sequences.

The patients in this study were chosen consecutively with obvious symptoms of left heart failure. In these cases, the accuracy of Simpson's disk method may deteriorate because the LV in short-axis view can no longer be approximated by a disk.

Conclusion

Simpson's disk method has comparable reproducibility with Simpson's rule. The two methods show reasonable agreement in both normal volunteers and patients. Therefore, Simpson's disk method may serve as an alternative for LV function and mass assessment if the LV maintains its original shape.

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