ASSESSMENT OF EJECTION FRACTION OF THE RIGHT AND LEFT VENTRICLES IN PATIENTS WITH ACUTE MYOCARDIAL INFARCTION BY MAGNETIC RESONANCE IMAGING

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Right and left ventricular function in acute myocardial infarction (AMI) was assessed by ECG-gated magnetic resonance imaging (MRI) in 64 patients and 8 volunteers. Five short axis images for intrinsic cardiac long-axis of the left ventricle were obtained at 9 msec and 309 msec after the R wave as end-diastole and end-systole. Right and left ventricular volumes were measured by Simpson's rule. The intraobserver variabilities in right and left ventricular ejection fraction (RVEF: $r=0.94$, LVEF: 0.89) were excellent. The interobserver variabilities in RVEF ($r=0.61$) and LVEF ($r=0.77$) were fair. LVEF, but not RVEF, was significantly reduced in patients with AMI. Among left ventricular dysfunction (LVEF $\leq 40\%$) patients, 50% exhibited right ventricular dysfunction (RVEF $\leq 40\%$). Among patients without left ventricular dysfunction, only 12% exhibited right ventricular dysfunction. In left ventricular and biventricular dysfunction compared with control, the left ventricular end-diastolic volume index increased (65 ± 10 ml/m², 68 ± 12 ml/m² vs 54 ± 8 ml/m²), the end-systolic volume index increased (40 ± 16 ml/m², 43 ± 7 ml/m² vs 18 ± 1 ml/m²), and the right ventricular end-diastolic volume index decreased (52 ± 13 ml/m², 53 ± 20 ml/m² vs 65 ± 8 ml/m²). MRI can thus be used to assess ventricular systolic function. Since patients with left ventricular dysfunction revealed a high incidence of right ventricular dysfunction, an interaction between the left and right ventricles may occur in ventricular dysfunction.

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LEF T ventricular volume and ejection fraction are useful parameters for evaluating cardiac function. They are determined by either cardiac catheterization, radionuclide ventriculography or echocardiography. The cardiac catheterization techniques are invasive and require the use of contrast media. Radionuclide ventriculography is non-

invasive but requires radiopharmaceutic preparations. Furthermore, although echocardiography is employed more frequently, the imaging quality is, to a great extent, dependent on obtaining an adequate cardiac window. Electrocardiography (ECG)-gated magnetic resonance imaging (MRI) has recently provided a new non-invasive method for determining ventricular volumes and ejection fractions^{1–5}

Right ventricular function has recently be-

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TABLE I CLINICAL CHARACTERISTICS OF THE STUDY SUBJECT

	<i>Acute myocardial infarction</i>		<i>Control</i>
	<i>Anterior</i>	<i>Inferior</i>	
<i>n</i>	37	27	8
<i>Age (yr)</i>	58±9	60±11	38±7
<i>Sex (male)</i>	32	23	7
<i>Days to MRI</i>	15±6	14±7	

MRI: Magnetic resonance imaging

come a subject of growing interest. The delay in recognizing the importance of right ventricular function may reflect the difficulty in measuring the volume. The complex structure of the right ventricle makes it difficult to assess without a Simpson's rule algorithm. However, MRI can provide an excellent contrast between the flowing blood and myocardium, and it can detect the heart from any direction or position. This technique thus offers a potential tool for determining both the right and left ventricular volumes⁶

The present study was undertaken to assess the reproducibility and accuracy of measurement of the right and left ventricular systolic function by ECG-gated MRI and to evaluate the right and left systolic ventricular function as well as the interaction between the left and right ventricles in patients with acute myocardial infarction (AMI).

METHODS

Subjects

The study subjects consisted of 64 patients with AMI (males: 55, females: 9), aged 59 ± 10 years. Their basic clinical characteristics are summarized in Table I. Diagnosis of AMI was based on the patient's clinical history (chest pain lasted for at least 30 min), typical evaluation of the serum creatine phosphokinase levels (≥ 2 times the normal upper range) and evolving ECG changes with or without the development of Q waves and ST elevation in at least 2 leads. Inferior myocardial infarction with right ventricular infarction was diagnosed from the following criteria: (1) ECG evidence of inferior ST elevation or the Q wave and V_{4R} ST eleva-

Fig.1. Short-axis images are shown at end-diastole (ED) in the top of the figure and at end-systole (ES) on the bottom of the figure.

tion ≥ 0.1 mV and (2) echocardiographic evidence of right ventricular free wall motion abnormalities. The criteria for exclusion were as follows: reinfarction, valvular disease, pulmonary disease and cardiomyopathy. The location of infarction was on the anterior wall (A-MI) in 37 cases, and on the inferior wall (I-MI) in 27 cases (6 cases with combined right ventricular infarction). MRI examinations were performed at 15 ± 6 days after onset in the A-MI group and 14 ± 7 days after onset in I-MI. Eight healthy volunteers with normal ECG and chest radiography pictures (aged 38 ± 7 years; males: 7 and females: 1) also underwent MRI studies as the control group.

Magnetic resonance imaging

Imaging was performed with a superconducting magnet operating at 1.5 tesla (Philips Gyroscan S-15). ECG-gated multislice and multiphase technique was used. Five slice images can each be obtained at 5 different

Fig.2. Intraobserver variability. **Panel A**, Correlation between first and second measurements of the left ventricular ejection fraction (LVEF) by the same observer. **Panel B**, Correlation between first and second measurements of the right ventricular ejection fraction (RVEF).

phases of the cardiac cycle using a pulse sequence with a spin-echo time (TE) of 30 and 60 msec (TE 30 msec images were used for analysis), 2 averages, 350 mm field of view and 10 mm slice thickness. The pulse repetition time was equal to the RR interval. The acquisition matrix was 128×128 , interpolated to 256×256 for display with a pixel size of 1.4 mm. The planning of 5 short-axis slices acquired from the transverse planar image. The heart from base to apex was divided into 5 short-axis slices; that is, based on the one most approximating the equatorial plane of the left ventricle, 5 short-axis planes were defined by 5 lines perpendicular to the ventricular septum and long axis from base to apex. To include both right and left ventricles on each short-axis, the slice factor was adjusted. There were 5 beating intervals, beginning at 9 msec after the R wave, and each subsequently displayed 100 msec; 9, 109, 209, 309, 409 msec. As end-diastolic and end-systolic images, the 9 msec and 309 msec images were used, respectively (Fig. 1). The right and left ventricular volumes were measured by a Simpson's rule algorithm. Employing a tracking-ball, the ventricular endocardial outlines were traced by hand. The end-diastolic volume (EDV) and end-systolic volume (ESV) of both ventricles were obtained, and then indexed to the body surface area. The stroke volume (SV) and ejection fraction of

the biventricle were calculated. The interobserver variability of the measurements was estimated in 33 of the 64 patients who were chosen at random. The measurements of volume and ejection fraction were taken by 2 investigators independently. The interobserver variability was estimated in all 72 subjects, i.e. 64 patients and 8 volunteers. The second measurement was performed approximately 1 month after the first.

Statistical analysis

All data are expressed as the mean $\pm$ standard deviation. Statistical correlations of the interobserver and intraobserver variability were evaluated by linear regression analysis. In addition, the standard error of estimate (SEE) was calculated as a measure of individual variability. Student's t test was employed to determine the statistical significance of data comparisons. Differences were considered significant at a p value of <0.05 .

RESULTS

Reproducibility and accuracy

We assessed the intraobserver and interobserver variability of the left and right ventricular ejection fraction (LVEF, RVEF) measurements. The intraobserver variability was low, as evidenced by very high correlation coefficients (LVEF: $r=0.89$, $p<0.01$, $SEE=3.4\%$; RVEF: $r=0.94$, $p<0.01$, SEE

Fig.3. Interobserver variability.

Panel A: Correlation of the left ventricular ejection fraction (LVEF) measured by two independent observers.

Panel B: Correlation of the right ventricular ejection fraction (RVEF) measured by two independent observers.

Fig.4. Correlation between the right and left ventricular stroke volumes (SV) measured by MRI.

=3.1%)(Fig. 2). The interobserver variability was also low, as evidenced by the correlation coefficients (LVEF: $r = 0.77$, $p < 0.01$, SEE = 6.3%; RVEF: $r = 0.61$, $p < 0.01$, SEE = 9.4%)(Fig. 3). The standard error of estimated ejection fraction in interobserver variability was higher than intraobserver variability. The standard error of estimated ejection fraction in interobserver variability was higher in the right ventricle than in the left ventricle. The accuracy of measurement of the right ventricle cannot be evaluated, since the measurement of the right ventricu-

TABLE II BIVENTRICULAR EJECTION FRACTIONS

	<i>n</i>	LVEF	RVEF
A-MI	37	53.0 ± 14.0**	49.9 ± 9.8
I-MI	27	54.4 ± 10.0*	50.1 ± 12.5
Control	8	64.0 ± 6.0	54.0 ± 2.5

*, $p < 0.05$, **, $p < 0.01$ compared with control.

LVEF: Left ventricular ejection fraction

RVEF: Right ventricular ejection fraction

A-MI: Anterior myocardial infarction

I-MI: Inferior myocardial infarction

lar volume is not established without Simpson's rule. We also assessed the correlation between the left ventricular stroke volume (LVSF) and the right ventricular stroke volume (RVSF). The correlation of these parameters was fairly positive ($r = 0.78$, $p < 0.01$, SEE = 5.8 ml)(Fig. 4).

Ejection fraction in patients and control group

The results for the ejection fraction are shown in Table II. LVEF was 64.0 ± 6.0% in the control group, 53.0 ± 14.0% in the A-MI group and 54.4 ± 10.0% in the I-MI group. RVEF was 54.0 ± 2.5% in the control group, 49.9 ± 9.8% in the A-MI group and 50.1 ± 12.5% in the I-MI group. Compared with

Fig.5. Summarized data for left and right ventricular dysfunction in 64 patients with acute myocardial infarction (AMI).

Fig.6. Ejection fraction data from a 58-year-old male with anterior acute myocardial infarction. LVEF was 21%; RVEF was 37%.

the control group, LVEF was significantly impaired in the A-MI group ($p < 0.01$) and in the I-MI group ($p < 0.05$), but no significant differences were observed for RVEF.

The data for ventricular dysfunction in the 64 patients are summarized in Fig. 5. In 7 of

the 14 patients (50%) with left ventricular dysfunction (LVEF $\leq$ 40%), right ventricular dysfunction (RVEF $\leq$ 40%) occurred simultaneously. Among these biventricular dysfunction patients (LVEF $\leq$ 40%, RVEF $\leq$ 40%), only one experienced combined inferior and right ventricular infarction, another one suffered from inferior myocardial infarction, and 5 patients suffered from anterior myocardial infarction. However, of the 50 patients without left ventricular dysfunction, only 6 (12%) exhibited right ventricular dysfunction. One of these 6 patients experienced combined inferior and right ventricular infarction, 3 patients suffered only from inferior myocardial infarction and 2 patients suffered from anterior myocardial infarction. The incidence of right ventricular dysfunction in patients with left ventricular dysfunction was 50%, which was significantly higher than that in those without left ventricular dysfunction ($p < 0.01$). Furthermore, biventricular dysfunction occurred in 13.5% (5/37) of the A-MI group and in 7.4% (2/27) of the I-MI group. There was no significant difference between the A-MI and I-MI groups.

A representative example of an AMI patient with biventricular dysfunction is illustrated in Fig. 6.

Ventricular volume index in patients and control group

Since EF is influenced by changes of EDV and ESV, the left and right ventricular volume indices were also studied (Table III).

The left ventricular end-diastolic volume index (LVEDVI) was 54 ± 8 ml/m² in the control group, 65 ± 10 ml/m² in patients with

TABLE III LEFT AND RIGHT VENTRICULAR VOLUME INDICES

<i>n</i>	<i>LVEF</i> ≤ 40%		<i>LVEF</i> > 40%		<i>Control</i> 8
	<i>RVEF</i> ≤ 40% 7	<i>RVEF</i> > 40% 7	<i>RVEF</i> ≤ 40% 6	<i>RVEF</i> > 40% 44	
<i>LVEDVI</i>	65 ± 10*	68 ± 12*	59 ± 13	50 ± 15	54 ± 8
<i>LVESVI</i>	40 ± 16*	43 ± 7***	28 ± 8**	21 ± 9	18 ± 1
<i>RVEDVI</i>	52 ± 13*	53 ± 20	74 ± 16	50 ± 11**	65 ± 8
<i>RVESVI</i>	35 ± 15	22 ± 7*	48 ± 10**	24 ± 7***	30 ± 3

*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$ compared with control.

LVEF: Left ventricular ejection fraction, *RVEF*: Right ventricular ejection fraction, *LVEDVI*: Left ventricular end-diastolic volume index, *LVESVI*: Left ventricular end-systolic volume index, *RVEDVI*: Right ventricular end-diastolic volume index, *RVESVI*: Right ventricular end-systolic volume index.

biventricular dysfunction, 68 ± 12 ml/m² in patients with only left ventricular dysfunction, 59 ± 13 ml/m² in patients with only right ventricular dysfunction, and 50 ± 15 ml/m² in patients without biventricular dysfunction. The left ventricular end-systolic volume index (*LVESVI*) was 18 ± 1 ml/m² in the control group, 40 ± 16 ml/m² in patients with biventricular dysfunction, 43 ± 7 ml/m² in patients with only left ventricular dysfunction, 28 ± 8 ml/m² in patients with only right ventricular dysfunction, and 21 ± 9 ml/m² in patients without biventricular dysfunction. Compared to the control group, the *LVEDVI* values in patients with biventricular dysfunction and in those with only left ventricular dysfunction were significantly larger ($p < 0.05$, $p < 0.05$). The *LVESVI* values in patients with biventricular dysfunction, with only left ventricular dysfunction and with only right ventricular dysfunction were significantly larger ($p < 0.05$, $p < 0.001$, $p < 0.01$).

The right ventricular end-diastolic volume index (*RVEDVI*) was 65 ± 8 ml/m² in the control group, 52 ± 13 ml/m² in the patients with biventricular dysfunction, 53 ± 20 ml/m² in the patients with only left ventricular dysfunction, 74 ± 16 ml/m² in the patients with only right ventricular dysfunction, and 50 ± 11 ml/m² in the patients without biventricular dysfunction. The right ventricular end-systolic volume index (*RVESVI*) was 30 ± 3 ml/m² in the control group, 35 ± 15 ml/m² in the patients with biventricular dysfunction, 22 ± 7 ml/m² in the patients with only left ventricular dysfunction, 48 ± 10 ml/m² in the patients with only right ven-

tricular dysfunction, and 24 ± 7 ml/m² in the patients without biventricular dysfunction. Compared to the control group, the *RVEDVI* value in patients with biventricular dysfunction was significantly smaller ($p < 0.05$), the *RVEDVI* value in the patients with only left ventricular dysfunction was also smaller but the difference was not significant. *RVESVI* values were smaller in the patients with only left ventricular dysfunction and without biventricular dysfunction ($p < 0.05$, $p < 0.01$) but were not significantly different in patients with biventricular dysfunction. *RVESVI* value in patients with only right ventricular dysfunction was larger ($p < 0.001$).

DISCUSSION

Gated cardiac MRI techniques are used to provide information concerning global and/or regional ventricular function. For the global function, end-diastolic and end-systolic volumes are evaluated. For the regional function, wall thickness, thickening and tissue characteristics are evaluated. The left and right ventricular volumes can be measured by employing either radionuclide ventriculography, echocardiography or contrast ventriculography. However, several limitations are encountered, such as the need for radionuclide pharmaceutical preparations, echo windows or radiation exposure. MRI can yield short-axis images of the ventricle with high resolution. Both ventricular volumes are then obtained by a Simpson's rule algorithm. The correlation between left ventricular volume by MRI and that by con-

trast ventriculography has been reported to be reasonably good^{7,8}. In our study, it was demonstrated that the reproducibility of measurement of left ventricular function by MRI was excellent.

It is more difficult to evaluate the right ventricular volume by the conventional methods without a Simpson's rule algorithm, due to (1) the overlapping of the right ventricle over the right atrium from the left anterior oblique projection, (2) the location of the right ventricle directly beneath the sternum, and (3) the irregular shape of the right ventricle. From this standpoint, MRI is a useful method since the heart can be detected from any direction and position⁶, so making it possible to evaluate the right ventricular functions. We measured the right ventricular stroke volume and ejection fraction by Simpson's rule. The reproducibility of measurement of the right ventricular ejection fraction by MRI was also studied, and the right and left ventricular stroke volume were compared. In general, the right ventricular stroke volume should be equal to the left ventricular stroke volume in normal volunteers. We found that the correlation between the left ventricular stroke volume and right ventricular stroke volume was good. The reproducibility and variability of the measurements of the right ventricular function were fair in our study. However, interobserver variabilities of the left and right ventricular ejection fraction were not as low as intraobserver variabilities. This unexpected result may be explained by 2 factors. Firstly, the multislice technique required to determine the area of the ventricle at 5 slices makes it slightly difficult to identify the margin of the ventricles, especially on basal slices, in some patients. Secondly, the number of patients used in evaluating variability was relatively small.

MRI is completely non-invasive, and it does not require radionuclide pharmaceutical preparations or radiation exposure. There is also no limit to the number of measurements that can be taken. Thus, MRI has distinct advantages over contrast ventriculography, two-dimensional echocardiography and radionuclide ventriculography for the evaluation of ventricular volumes and/or ejection fraction. MRI is clearly a feasible method for measuring both ventricu-

lar volumes. However, MRI does need an adequate acquisition time (30–40 min) and expensive equipment. In measuring ejection fraction and ventricular volume, there is a positive correlation between using contrast ventriculography and MRI^{2,7}. For patients with less than 40% of left ventricular ejection fraction measured by contrast ventriculography, the prognosis was significantly worse than that for patients without dysfunction. Thus, subjects were classified into 2 groups, those with or without dysfunction, by a 40% ejection fraction.

In our study, in order to obtain true short-axis images, series transaxial images were acquired by planning from conventional coronal image. The transaxial images, through the intrinsic cardiac long-axis, provided a display of the four cardiac chambers. Then, we planed the 5 short-axis image planes on the one most approximating the equatorial plane of the left ventricle and defined to short-axis planes perpendicular to intrinsic cardiac long-axis from apex to base of the left ventricle. It is difficult to distinguish between right atrium and right ventricle by wall thickness on MRI. In cases which basal image showed left atrium, the patient was excluded from analysis.

Since the nadirs of the right and left ventricular volume curves were usually found in the same time frame³, right and left ventricular volumes were calculated simultaneously. In this study the end-diastolic images were obtained at 9 msec after the R wave. The end-systolic images were selected from 5 consecutive images acquired at 100 msec intervals. We employed an image at 309 msec after the R wave for the end-systole, for the following 2 reasons. Firstly, in the previous study⁹, the volume-time curve was composed of at least 8 measuring points in a cardiac cycle. There are good coefficients between 8 point measuring and original consecutive 30 msec measuring in ejection fraction and time to peak ejection fraction for index of systolic function. So, it is possible to accurately calculate ejection fraction by 100 msec to 120 msec frames interval. Secondly, ejection time from end-diastole to end-systole is usually about 300 msec and isonitrile diastole continues for another 50–60 msec.

Right ventricular dysfunction coexisted in some patients with left ventricular dysfunc-

tion due to myocardial infarction. This fact suggests that an interaction may exist between the left and right ventricles. The left ventricular pump function has an influence on the right ventricular performance.¹⁰ Right ventricular performance is influenced by (1) intrinsic factors, such as the contractile state of the right ventricle,¹¹ and (2) extrinsic factors, such as loading conditions, constraining effects of the pericardium,^{12,13} and the contribution of the interventricular septum to the right ventricular work.^{14,15} The common muscle fibers that encircle both the right and left ventricles also play a minor role. In particular, the septum has an important role in both left and right ventricular performance. Right ventricular systolic pressure generation and performance are dependent, to a large extent, on left septum contractile contributions. In anterior infarction, when the septum contractile markedly diminishes, right ventricular dysfunction can be observed. In inferior infarction, the septum contractile is not decreased, and so left ventricular dysfunction is rarely observed.

The study by Elzinga et al illustrated this left to right interaction.¹⁶ An isovolumic left ventricular contraction, at a high left ventricular pressure, results in an enhanced right ventricular pump function as compared to when the left ventricle ejects at a low pressure level. Based on our data, LVEDVI and LVESVI were significantly increased and RVEDVI was decreased in left ventricular dysfunction. It might be considered that an increased left ventricular end-diastolic volume impairs right ventricular, the right ventricular end-diastolic volume would then be reduced, thus reducing both LVEF and RVEF. When contraction of the right ventricle can be compensated, and right ventricular end-systolic volume simultaneously decrease, it may remain functional. In these cases, LVEF was reduced but RVEF remained normal.

In this study, RVEDVI and RVESVI in patients with normal biventricular function were lower compared to the control group. One reason for this may be that the average age of the control group was younger. Other reasons remain unclear and further study is necessary.

In patients with biventricular dysfunction, there is no relationship to the location of

myocardial infarction. This suggests that no matter where the infarction occurs, one side's ventricular dysfunction may affect the other side's performance.

Based on the present results, MRI can be useful in determining right and left ventricular function, the technique appears to be more practical for clinical application since it can be used repeatedly and is non-invasive. Furthermore, as patients with left ventricular dysfunction revealed a high incidence of right ventricular dysfunction, suggesting the possibility of some interaction between the left and right ventricles, it is important to determine both ventricular functions, particularly in cases of left ventricular dysfunction.

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