Journal of Cardiology 19: 911-920, 1989

Quantitative evaluations of left ventricular function obtained by electrocardiographically-gated magnetic resonance imaging

Tohru TAKEDA
Mitsuo MATSUDA*
Takao AKATSUKA**
Kaname IIDA
Yasuro SUGISHITA
Izumi ANNO
Masayoshi AKISADA
Susumu KOSEKI***

Summary

Using electrocardiographically-gated magnetic resonance imaging, regional cardiac function was evaluated in 12 normal volunteers and in 10 cases of old myocardial infarction. The optimal short axis of the left ventricle was selected at the chordae tendineae level. The left ventricle was divided into 12 segments using a computer-aided system, and percentile shortening fraction (%SF) and percentile wall thickening (%WT) were calculated in each segment by the fixed coordinate method.

In the normal volunteers, heterogeneity of both %FS and %WT was observed, ranging from 25±13% and 37±13%, respectively in the septal segment, to 49±13% and 60±21%, respectively in the posterior segment. In the cases of myocardial infarction, decreased %FS and %WT were detected at the affected regions. The abnormal regions revealed by %WT tended to be narrower than those revealed by %FS. Thus the MR technique at the optimal axis may be useful for quantitative evaluations of regional cardiac function.

Key words
Quantitative evaluation Left ventricular function Magnetic resonance imaging Wall motion Wall thickening

筑波大学　臨床医学系
*同　体育科学系
つくば市天王台 1-1-1 (〒305)
**山形大学　工学部情報工学科
米沢市 (〒992)
***筑波記念病院
つくば市大穂 (〒305)

Institute of Clinical Medicine, and *Institute of Sport and Science, University of Tsukuba, Tennodai 1-1-1, Tsukuba 305
**Department of Information Engineering, Yamagata University, Yonezawa 992
***Tsukuba Memorial Hospital. Tsukuba 305

Received for publication December 6, 1988; accepted February 17, 1989 (Ref. No. 34-PS20)

Introduction

Electrocardiographically (ECG)-gated magnetic resonance imaging (MRI) clearly demonstrates cardiac chambers and cardiac walls without the use of contrast material1,2), and such imaging appears to be well suited for the study of regional left ventricular (LV) contraction. Regional asymmetries of LV wall motion and thickening generally indicate myocardial ischemia or infarction, or both3~5). Earlier magnetic resonance examinations for evaluating cardiac function were not performed in planes orthogonal to the myocardium6,7). However, in the present study, an optimal short-axis image was obtained using electronic axial rotation. The percentile changes in regional wall thickening and wall motion at end-diastole and end-systole were quantitatively analyzed to assess regional myocardial function.

Methods

1. Subjects

MRI examination was performed for normal volunteers and a group of ischemic patients. The normal group consisted of 11 men and one woman whose ages ranged from 20 to 33 years (26±3, mean±SD). None of the volunteers had histories of cardiac disease, and results of their physical examinations, chest radiography, and electrocardiography were normal. The ischemic group consisted of seven men and three women with old anterior myocardial infarction, whose ages ranged from 45 to 82 years (61±14, mean ±SD). Echocardiography and ECG-gated MRI were performed within 48 hours to evaluate the segmental myocardial function of the left ventricle.

2. Magnetic resonance imaging (MRI)

The MRI unit (Hitachi G-10) had a 0.15 tesla magnet. An electrocardiographic signal was obtained from standard surface electrodes placed on both shoulders and over the right distal portion of the chest. Gating was accomplished using the patient's ECG signal coupled with the imaging system. For the end-diastolic image, gating was triggered at the rising point of the QRS complex. For the end-systolic image, gating was triggered at the beginning of the down slope of the T-wave. Repetition time corresponded to the heart rate. A spin echo pulse sequence between 90 and 180 pulses with a 40 msec delay was used for the MRI. The slice thickness was 15 mm.

Optimal short-axis images at end-diastole and end-systole were obtained using an electronic oblique technique similar to the two-dimensional echocardiogram at the level of the chordae tendineae. The imaging procedures were as follows:

To obtain the long-axis orientation of the heart, the imaging technique required initial acquisition of a transverse set of multisection images where the apex, aortic valve, and septal plane had to be specified. Then, by the electronic oblique technique, the vertical long-axis image of the LV could be obtained. Secondly, the horizontal long-axis image was obtained using the previously determined vertical long-axis image and by orienting the apex and aortic valve. If no significant deformity could be demonstrated in the four-chamber view, the short-axis planes were taken as orthogonal to the horizontal and vertical long-axis images (**Fig. 1**).

3. Echocardiography

Using the Aloka SSD-810, two-dimensional echocardiograms were recorded to evaluate the dimensions obtained by magnetic resonance images. Studies were performed with patients in the left lateral decubitus position, using standard techniques. Short-axis parasternal images were obtained at the levels of the chordae tendineae.

4. Analyzing procedure

The procedures for measuring MRI were similar to those for echocardiography. The dimensions of the left ventricle were determined along a line perpendicular to the septum and posterior wall. The endocardial and epicardial boundaries of the left ventricle were traced manually and digitized using a tablet digitizer. The center of gravity of the epicardial boundary at end-diastole was calculated by computer (HP-1000F). From this center, 12 radii at 30

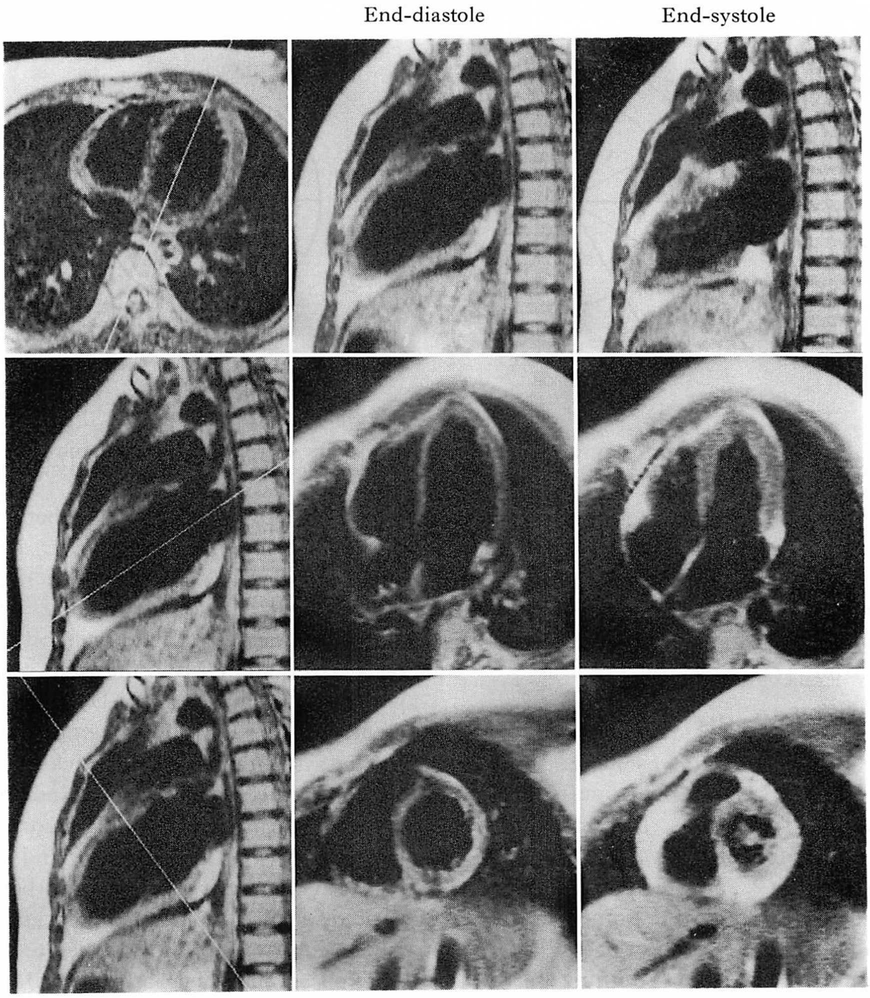


Fig. 1. Magnetic resonance imaging with optimal axis in a normal subject.
Images at the vertical long-axis, horizontal long axis and short axis are demonstrated at the end-diastolic and end-systolic phases.

degree intervals were generated, then the short-axis image was divided into 12 equal LV cavity and LV wall segments. Segments 1 to 3 corresponded approximately to the posterior wall, 4 to 6, to the anterior wall; 7 to 9, to the septum; and 10 to 12, to the inferior wall (**Fig. 2**). Percentile shortening fraction (%FS) and percentile wall thickening (%WT) were calculated both by echocardiography and MRI using the following formulae:

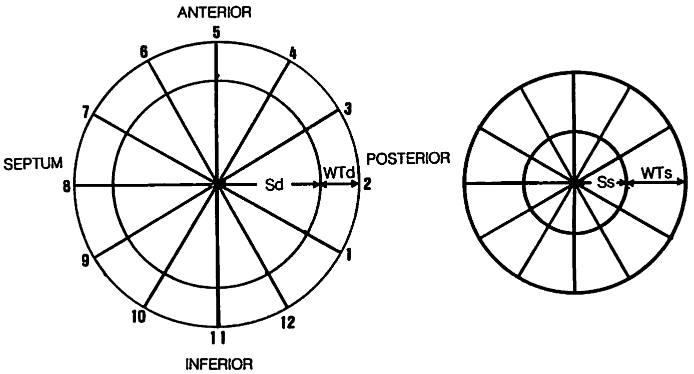
$$\%FS=(Sd-Ss)/Sd\times 100$$

$$\%WT=(WTs-WTd)/WTd\times 100$$

where Sd and Ss corresponded to end-diastolic and end-systolic dimensions of the left ventricle, respectively. WTd and WTs corresponded to wall thickening at the end-diastolic and end-systolic phases, respectively.

5. Statistics

The mean value and standard deviation for each cardiac dimension were calculated sepa-



End-diastole End-systole

Fig. 2. Schematic diagram of the measurements of regional dimensions.

rately from the echocardiogram and the magnetic resonance image. For comparisons of the two techniques, paired t-tests were used. Linear regression analysis was also performed on the cardiac dimensions obtained by echocardiography and MRI.

Results

1. Quality of the magnetic resonance image

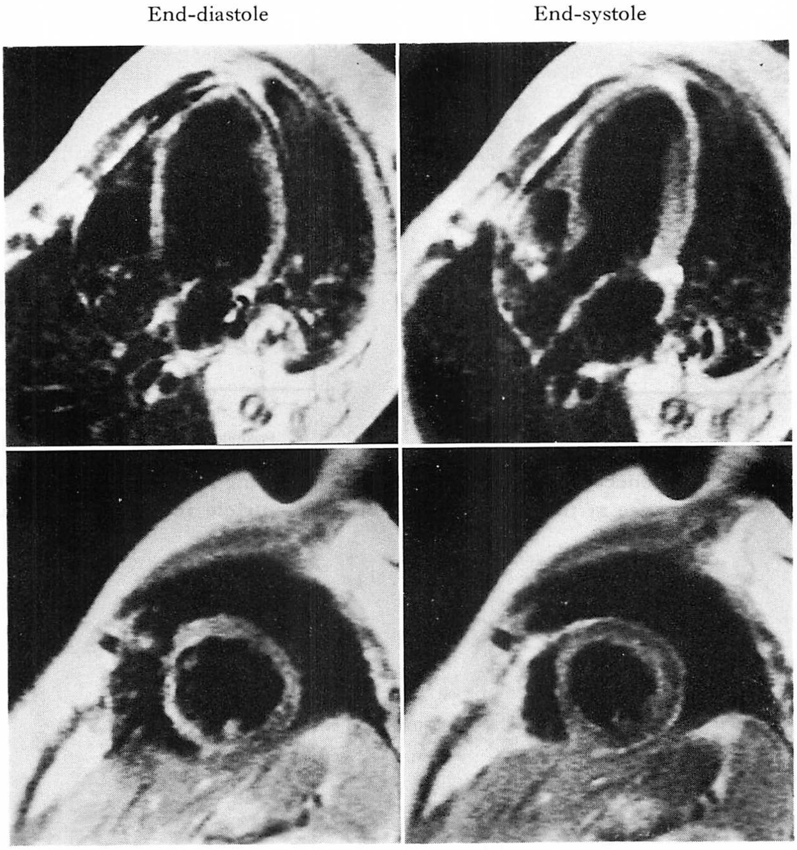
MRI resulted in a cardiac image sufficiently clear for quantitative analysis. In normal subjects, the ventricular chamber appeared as a void in signal intensity, and the ventricular wall was clearly demonstrated. But some subjects exhibited a slight blur in the inferior wall. The normal subjects did not show thinning of the cardiac wall at the end-diastolic phase; wall thickening was evident at the end-systolic phase (**Fig. 1**). However, in cases of anterior myocardial infarction, wall thinning was demonstrated in the infarcted regions at the end-diastolic phase. Furthermore, wall thickening was not observed at the end-systolic phase (**Fig. 3**).

2. Comparisons of dimensions obtained by MRI and echocardiography

The results of parameters according to measurements by MRI and echocardiography in systole and diastole are summarized in **Table 1**. Left ventricular dimension obtained by MRI was 49±4.0 mm in end-diastole. A good correlation ($r=0.80$) was observed between the two images. However, left ventricular dimensions in end-systole and %FS showed a moderate correlation with the corresponding values as obtained by echocardiography ($r=0.66$ and 0.61, respectively). On MRI, diastolic wall thickness was 9.6±1.1 mm (mean±SD) in the septal segment, and 9.9±0.9 mm in the posterior segment. In the systolic phase, wall thickness was 13.7±1.2 mm in the septal segment, and 15.1±1.2 mm in the posterior segment. Good correlations ($r=$ 0.87 and 0.79 at end-diastole and end-systole, respectively) were also observed between magnetic resonance and echocardiographic measurements in the septum. Moderate correlations were observed in the posterior wall ($r=0.69$ and 0.74 at end-diastole and end-systole, respectively).

3. Regional myocardial function by MRI

The values of % wall thickening and % shortening of the septum were less than those of other regions (**Fig. 4**). Regional % shortening was 49±13% at the posterior wall, 46±11% at the anterior wall, 25±13%at the septum, and 29±14% at the inferior wall. Regional % wall thickening was 60±21% at the posterior, 51±28% at the anterior wall, 37±13% at the septum, and 63±38% at the inferior wall. Heterogeneity of %WT and %FS was observed between the segments. The difference in %WT between the septum and posterior wall was not



End-diastole

End-systole

Fig. 3. Magnetic resonance imaging in the case of anterior myocardial infarction.
Wall thinning can be seen in the septum and apex at the end-diastolic phase. Systolic myocardial wall thinning is also revealed in these regions.

Table. 1. Comparison of measurements obtained by magnetic resonance imaging and echocardiography

	MRI	Echo	r
Left ventricle (diastole) (mm)	49±4.0	48±3.6	0.80
(systole) (mm)	32±2.6	32±2.4	0.66
Shortening fraction (%)	34±3.1	33±3.4	0.61
Septal thickness (diastole) (mm)	9.6±1.1	8.7±1.2	0.87
(systole) (mm)	13.7±1.2	12.0±1.4	0.79
% Wall thickening (%)	43±14	39±14	0.76
Posterior wall thickness (diastole) (mm)	9.9±0.9	9.6±0.9	0.69
(systole) (mm)	15.1±1.2	14.9±1.5	0.74
% Wall thickening (%)	54±13	56±11	0.60

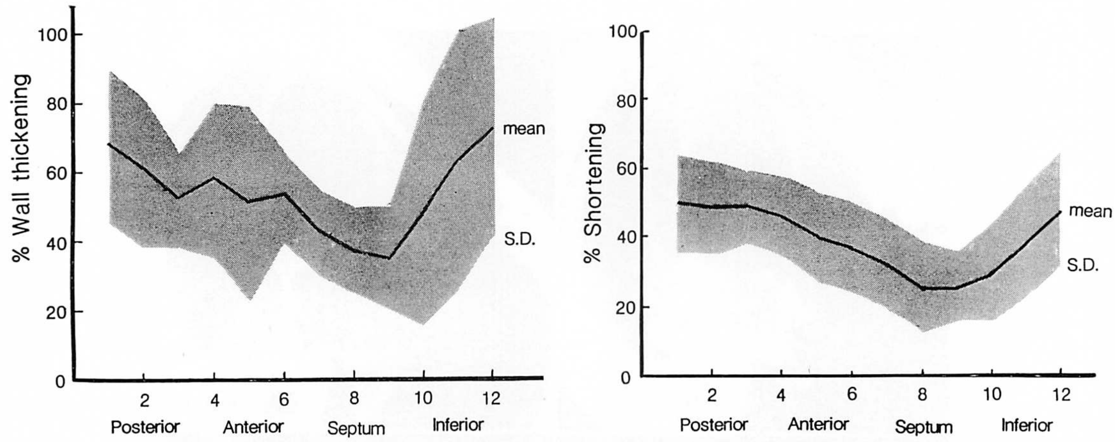


Fig. 4. Regional differences in percentile fractional shortening and percentile wall thickening around the circumference at the short axis of the left ventricle in 12 normal volunteers.

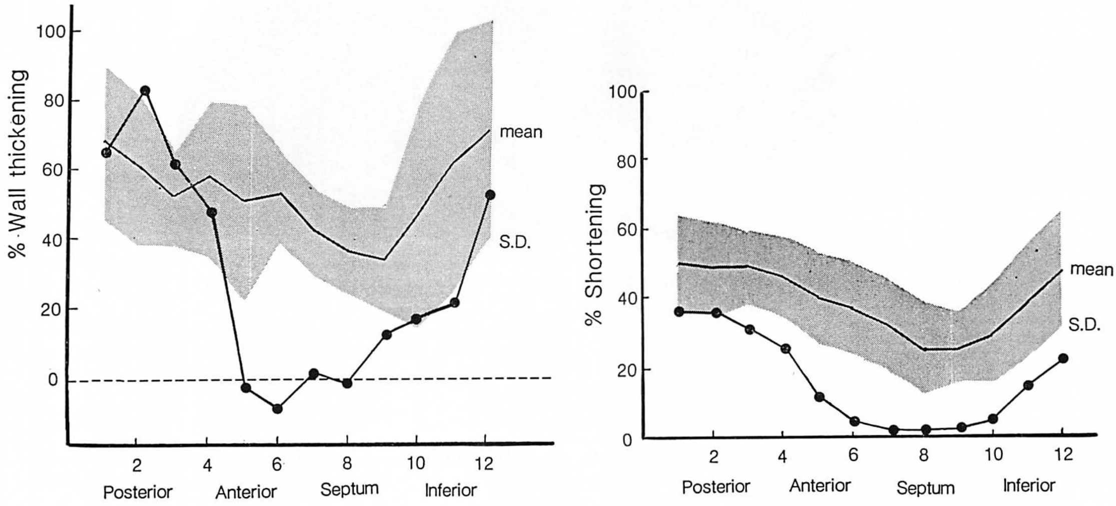


Fig. 5. Regional differences in percentile fractional shortening and percentile wall thickening around the circumference at the short axis of the left ventricle in a case of anterior myocardial infarction.

The abnormal segments detected by %WT tended to be narrower than those detected by %FS.

statistically significant, but with the %FS, a difference was observed.

The results of quantitative analysis in cases of anterior myocardial infarction are shown in **Fig. 5**. Decreased % wall thickening and % shortening were clearly observed at the anteroseptal wall.

The number of abnormal segments detected by analysis of % wall thickening and % shortening is shown in **Fig. 6**. Fifty of the 120 segments were abnormal by the % wall thickening analysis ; whereas 64 segments were ab-

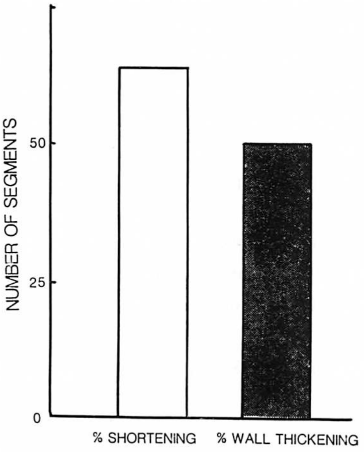


Fig. 6. The number of abnormal segments in 10 cases of anterior myocardial infarction.

normal by the % shortening analysis. A chi-square test between % wall thickening and % shortening was not statistically significant. However, the total number of abnormal segments revealed by % wall thickening was slightly less than that revealed by % shortening.

Discussion

ECG-gated MRI of the left ventricle at the optimal axis angle clearly demonstrated the cardiac chamber and cardiac wall at the end-diastolic and end-systolic phases. The inherent contrast between the blood pool and the myocardium allows the determination of myocardial wall thickening and wall motion, from which an index of regional ventricular function can be derived. In cases of old myocardial infarction, regional wall thinning resulting in wall motion abnormality was detected in the infarcted regions. Higgins et al. reported the same results using MRI[1,2]. In some cases, a slightly blurred image was observed in the inferior wall. This might have been caused by motion of the diaphragm due to respiration.

To perform quantitative regional analyses, the accuracy of cardiac dimensions as obtained by MRI was evaluated by comparing them with those obtained by echocardiography. During this comparison, the dimensions obtained by MRI corresponded well with those obtained by echocardiography. Friedman et al[8] reported that, for normal subjects, MRI and two-dimensional echocardiography yielded values for cardiac dimensions with similar standard deviations. They also reported that poor correlation was observed between the two techniques as to posterior wall thickness and systolic dimensions. However, results of the present study showed moderate to good correlations for these parameters. Dimensional errors are probably due to the fact that in earlier reported studies, the angle to the heart had not been corrected, and this may have been minimized during our examinations by the use of optimal axis angles[8~11]. With these improvements, the regional quantitative analysis appears adequate for evaluating regional cardiac function.

In the current study, substantial variability of %WT and %FS was observed among the myocardial segments in the group of normal volunteers. The % WT in normal subjects (ranging from 35±15% in the septum to 72±32% in the posterior wall) did not statistically differ significantly between the regions. However, there were considerable variations in the %FS, ranging from 25±10% at the septum to 50±14% at the posterior wall. The observation of considerable heterogeneity in %FS and % wall thickening when determined by echocardiography, was also previously noted both in animal and human studies[12,13]. In particular, relatively high %FS and %WT values have been reported in the posterior segments[13].

The factors which contribute to non-uniformity or heterogeneity of left ventricular contraction in each segment can be broadly classified as physiologic and technical[12,14] :

1. Physiologic factors include the variable time of left ventricular activation[15], variable left ventricular regional flow[16], regional anatomy (fiber orientation and wall thickness)[17] and external factors (right ventricular pressure and intrathoracic pressure). As a consequence of these physiologic factors, there is no reason to expect the left ventricle to contract in a manner

which is temporally or geometrically homogeneous.

2. Technical factors are related to the complex motion of the heart in three dimensions and conformational changes which occur during its contraction. These include translation, rotation, base-to-apex shortening along the ventricular long axis, and differential rotation among levels. Moreover, the problems of accurate recognition of borders, image registration and constraints of the reference system used to analyze the data likewise contribute significantly to artifacts in data analysis.

Infarcted segments in patients with ischemic heart disease reduced % systolic wall thinning and were often combined with diastolic wall thinning. The abnormal regions shown by %WT were narrower than those revealed by %FS in each case. The numbers of abnormal segments which were identified by %FS, tended to be much greater than those identified by %WT. Therefore, %WT may be more sensitive in revealing ischemic regions. Vatner has shown that endocardial shortening decreases as little as a 19～20% with reduction in blood flow[18]. Gallagher has also shown that when perfusion is decreased only to the inner half of the myocardium, reduction up to 75% in systolic wall thickening may occur. Akinetic wall motion may be observed when perfusion remains normal in the subepicardial one-fourth of the wall. Dyskinesis occurs when blood flow is reduced transmurally[19]. Furthermore, Lieberman et al concluded that endocardial wall motion as assessed by echocardiography was less sensitive in discriminating infarcted from non-infarcted myocardium than the measurement of systolic wall thickening, resulting in overestimates of true infarct size[20].

Cross-sectional echocardiography[3,12,13] and cine computed tomography[14,21] were previously reported useful for assessing wall motion and systolic myocardial wall thickening, but each of these techniques has inherent limitations. Echocardiography relies on ideal accoustic conditions for image acquisition, and cine computed tomography, which provides a high resolution tomographic image, requires the intravenous injection of iodinated contrast material and exposure to radiation. Conventional MRI has excellent spatial resolution and does not require contrast agents for obtaining the blood pool, but it has limited temporal resolution and requires a long imaging time. Today other MRI techniques are being investigated to analyze cardiac function more precisely[22], and through this, the problems of temporal resolution and long imaging acquisition time may be overcome.

心電図同期磁気共鳴画像による左室機能の定量的評価

筑波大学　臨床医学系，*体育科学系
**山形大学　工学部情報工学科
***筑波記念病院
武田　徹，松田光生*，赤塚孝雄**，
飯田　要，杉下靖郎，阿武　泉，
秋貞雅祥，小関　迪***

心電図同期 magnetic resonance imaging (MRI) を用い局所心機能解析を試みた．対象は健常ボランティア 12 例，および陳旧性前壁心筋梗塞 10 例である．本研究では，傾斜磁場法を用い最適な心短軸を腱索部に設定し，収縮終期および拡張終期に対応する画像を収集した．超音波法で求めた中隔および後壁部での壁厚と左室内径の計測値は，MRI で求めたそれと良く対応し，MRI を用いた定量的解析が可能であると考えられた．そこで，拡張終期における重心点を基準とした局所壁収縮率 (%FS) および，局所壁厚変化率 (%WT) を求め，局所心機能の指標とした解析を行った．

健常例では，拡張終期における局所壁の非薄化は認められず，収縮終期における著明な壁厚増加が見られた．中隔での %FS, %WT は 25±13, 37±13%，後壁では 49±13, 60±21% で，局所壁収縮における不均一性が示された．陳旧性前壁心筋梗塞では，梗塞部位における壁の非薄化，および収縮期における壁厚増加の消失ないし低下が示された．虚血部における %WT は %FS より領域が狭く，%WT は虚血部位の広がりをより鋭

敏に描出する可能性が示された．心臓本来の軸補正を加味した心電図同期 MRI を用いて，局所心機能の定量的解析の有効性が示された．

Acknowledgments

We thank Masaya Igarashi MD, University of Tsukuba, and Takanori Nakajima of Yamagata University for their assistance in computer programming, and Takuo Shimada and Toshikazu Suzuki RT, for their technical assistance.

References

1) Higgins CB, Lanzer P, Stark D, Botvinick E, Schiller NB, Crooks L, Kaufman L, Lipton MJ: Nuclear magnetic resonance imaging in patients with chronic ischemic heart disease. Circulation **69**: 523-531, 1984

2) Akins EW, Hill JA, Sievers KW, Conti CR: Assessment of left ventricular wall thickness in healed myocardial infarction by magnetic resonance imaging. Am J Cardiol **59**: 24-28, 1987

3) Parisi AF, Moynihan PF, Folland ED, Feldman CL: Quantitative detection of regional left ventricular contraction abnormalities by two-dimensional echocardiography. II. Accuracy in coronary artery disease. Circulation **63**: 761-767, 1981

4) Sasayama S, Franklin D, Ross JJr, Kemper WS, McKown D: Dynamic changes in left ventricular wall thickness and their use in analyzing cardiac function in the conscious dog. Am J Cardiol **38**: 870-879, 1976

5) Eber LM, Greenberg HM, Cooke JM, Gorlin R: Dynamic changes in left ventricular free wall thickness in the human heart. Circulation **39**: 455-464, 1969

6) Fisher MR, Von Schulthess GK, Higgins CB: Multiphasic cardiac magnetic resonance imaging: Normal regional left ventricular wall thickening. Am J Roentgenol **145**: 27-30, 1985

7) White RD, Cassidy MM, Cheitlin MD, Emilson B, Ports TA, Lim AD, Botvinick EH, Schiller NB, Higgins CB: Segmental evaluation of left ventricular wall motion after myocardial infarction: Magnetic resonance imaging versus echocardiography. Am Heart J **115**: 166-175, 1988

8) Friedman BJ, Waters J, Kwan OL, DeMaria AN: Comparison of magnetic resonance imaging and echocardiography in determination of cardiac dimensions in normal subjects. J Am Coll Cardiol **5**: 1369-1376, 1985

9) Dinsmore RE, Wismer GL, Levine RA, Okada RD, Brady TJ: Magnetic resonance imaging of the heart: Positioning and gradient angle selection for optimal imaging planes. Am J Roentgenol **143**: 1135-1142, 1984

10) Feiglin DH, George CR, Maclntyre WJ, Donnell JK, Go RT, Pavlicek W, Meaney TF: Gated cardiac magnetic resonance structural imaging: Optimization by electronic axial rotation. Radiology **154**: 129-132, 1985

11) Kaul S, Wismer GL, Brady TJ, Johnston DL, Weyman AE, Okada RD, Dinsmore RE: Measurement of normal left heart dimensions using optimally oriented MR images. Am J Roentgenol **146**: 75-79, 1986

12) Pandian NG, Skorton DJ, Collins SM, Falsetti HL, Burke ER, Kerber RE: Heterogeneity of left ventricular segmental wall thickening and excursion in 2-dimensional echocardiograms of normal human subjects. Am J Cardiol **51**: 1667-1673, 1983

13) Haendchen RV, Wyatt HL, Maurer G, Zwehl W, Bear M, Meerbaum S, Corday E: Quantitation of regional cardiac function by two-dimensional echocardiography: I. Patterns of contraction in the normal left ventricle. Circulation **67**: 1234-1245, 1983

14) Feiring AJ, Rumnerger JA, Reiter SJ, Collins SM, Skorthon DJ, Rees M, Marcus MU: Sectional and segmental variability of left ventricular function: Experimental and clinical studies using ultrafast computed tomography. J Am Coll Cardiol **12**: 415-425, 1988

15) Marier DL, Gibson DG: Limitations of two frame method for displaying regional left ventricular wall motion in man. Br Heart J **44**: 555-559, 1980

16) Falsetti HL, Carroll BJ, Marcus ML: Temporal heterogeneity of myocardial blood flow in anesthetized dogs. Circulation **52**: 848-853, 1975

17) Greenbaum RA, Ho SY, Gibson DG, Becker AE, Anderson RH: Left ventricular fibre architecture in man. Br Heart J **45**: 248-263, 1981

18) Vatner SF: Correlation between acute reductions in myocardial blood flow and function in conscious dogs. Circ. Res **47**: 201-207, 1980

19) Gallagher KP, Kumada T, Koziol JA, McKown MD, Kemper WS, Ross J Jr: Significance of regional wall thickening abnormalities relative to transmural myocardial perfusion in anesthetized

dogs. Circulation **62**: 1266-1274, 1980

20) Lieberman AN, Weiss JL, Jugdutt BI, Becker LC, Bulkley BH, Garrison JG, Hutchins GM, Kallman CB, Weisfeldt ML: Two-dimensional echocardiography and infarct size: Relationship of regional wall motion and thickening to the extent of myocardial infarction in the dog. Circulation **63**: 739-746, 1981

21) Lanzer P, Garrett J, Lipton MJ, Gould R, Sievers R, O'Connell W, Botvinick E, Higgins CB: Quantitation of regional myocardial function by cine computed tomography: Pharmacologic changes in wall thickness. J Am Coll Cardiol **8**: 682-692, 1986

22) Pflugfelder PW, Sechtem UP, White RD, Higgins CB: Quantification of regional myocardial function by rapid cine MR imaging. Am J Roentgenol **150**: 523-529, 1988