Journal of Cardiography 15: 1187-1198, 1985

Effectiveness of ECG-gated magnetic resonance imaging in diagnosing cardiovascular diseases

Junichi NISHIKAWA
Tohru OHTAKE
Kikuo MACHIDA
Masahiro IIO
Nobuo YOSHIMOTO*
Tsuneaki SUGIMOTO*

Summary

Nuclear magnetic resonance imaging (MRI) is a noninvasive method which can discriminate between flowing blood and vascular walls, and is expected to contribute to the diagnosis of cardiovascular diseases. Since the data acquisition by conventional MRI is too long for precise cardiac imaging, the ECG-gated method is mandatory in evaluating cardiac function and producing cardiac images of high quality. To evaluate the effectiveness of ECG-gated MRI, left ventricular wall motion and ejection fraction by MRI were compared with those obtained by radionuclide technique. Two types of MR imagers were used: one with a resistive magnet (0.15 Tesla) for 12 patients, and the other with a superconductive magnet (0.35 Tesla) for eight patients. MRI imaged cardiac muscle and vascular walls without the need for any contrast media or radionuclides. The superconductive apparatus provided better quality images than did the resistive one. Comparing MRI with radionuclide technique regarding left ventricular wall motion, resistive and superconductive MRI data correlated satisfactorily with those of radionuclide technique, except in the inferior wall, which was better evaluated by radionuclide technique. Left ventricular ejection fraction obtained by MRI was moderately lower than those obtained by radionuclide technique, though the correlation was good [r=0.84 (resistive unit) and r=0.85 (superconductive unit)]. In addition to three-dimensional morphological information, ECG-gated MRI provides information nearly comparable to that of radionuclide technique in the evaluation of left ventricular function and wall motion. Therefore, we regard gated MRI as effective in evaluating various aspects of cardiovascular diseases.

Key words

ECG-gated magnetic resonance imaging (MRI) Cardiovascular nuclear medicine

---

Department of Radiology and *the Second Department of Internal Medicine, Faculty of Medicine, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113

Received for publication April 19, 1985; accepted June 1 1985 (Ref. No. 29-K7)

Introduction

Good quality examinations are minimally invasive and provide clear images and sufficient information for the physician to accurate diagnosis. The diagnostic imaging techniques for cardiovascular diseases include contrast angiography, X-ray CT, and nuclear medicine. Each of these modalities has its own advantages, but all of them involve ionizing radiation exposure and use of contrast media or radionuclides which can cause severe side effects including shock. Echocardiography is a non-invasive imaging modality, which require technical skill and expeniences in its interpretation. The recently developed nuclear magnetic resonance imaging (MRI) involves no ionizing radiation exposure or other hazards, and provides objective three-dimensional images. Its diagnostic capabilities have been documented in neurology, especially in evaluating the posterior fossa, the spine and the spinal canal. MRI is also expected to be diagnostically effective for cardiovascular diseases due to its ability to discriminate flowing blood from the vascular wall. However, the data acquisition time of conventional MRI is too long to provide clear cardiac images; therefore, the gated method is mandatory to evaluate cardiac function and to obtain cardiac images of good quality. The present study was designed to determine the effectiveness of ECG-gated MRI, comparing with established techniques in cardiovascular nuclear medicine.

Methods and Materials

MR imagers

We have used two types of MRI apparatus clinically; one, with a resistive magnet; the other, with a superconductive magnet. The resistive apparatus had a 0.15 Tesla magnet, and required an inversion recovery (IR) pulse sequence for gated heart studies to distinguish the cardiac pool from muscle. The superconductive apparatus was operated at 0.35 Tesla and required a spin-echo pulse sequence to distinguish the cardiac blood pool from heart muscle. Single-slice images produced by the resistive magnet apparatus and multiple images from the superconductive apparatus were used. The images of both units were reconstructed using the 2-dimensional (2D) Fourier transformation imaging techniques. Images were based on a 256×256 matrix. The thickness of the slices made by the resistive and superconductive magnet apparatus was 15 and 10 mm respectively.

Imaging technique

Images can be obtained by resistive magnet imager using saturation recovery (SR) and inversion recovery (IR), but the former cannot distinguish the blood flow from the vascular walls, probably due to short T_E. The former pulse sequence was used to select slices because of its short acquisition time. In the inversion recovery scan, T_I was 400 msec; and T_E, 13 msec. For end-diastolic images, we obtained an echo-signal at the R wave, and the time delay between the Rwave and the 180° pulse was set at the RR time interval minus 413 msec. End-systolic images were obtained in the same way at the T wave (**Fig. 1**). With the superconductive MR imager, only the spin-echo technique with T_E of 35 and 70 msec was used; a T_R of 200 msec was used to select slices. To obtain end-diastolic images, a 90° pulse was applied at half the maximum height of the R wave for an echo-signal near the R wave. End-systolic images were made by applying a 90° pulse at RT time minus 35 msec (**Fig. 2**). The data acquisition time using the resistive magnet MRI was four to six minutes per slice, and the reconstruction time was one minute per slice. With superconductive MRI, the time for data acquisition was 10 to 15 minutes for three to four slices, and the reconstruction time was eight seconds per slice.

Evaluation of the left ventricle

Left ventricular wall motion abnormalities were evaluated by displaying the end-diastolic and end-systolic images reciprocally on the CRT. The left ventricular ejection fraction was calculated by obtaining the left ventricle volume using the area-length method.

Radionuclide technique

The multigated blood-pool scan was obtained

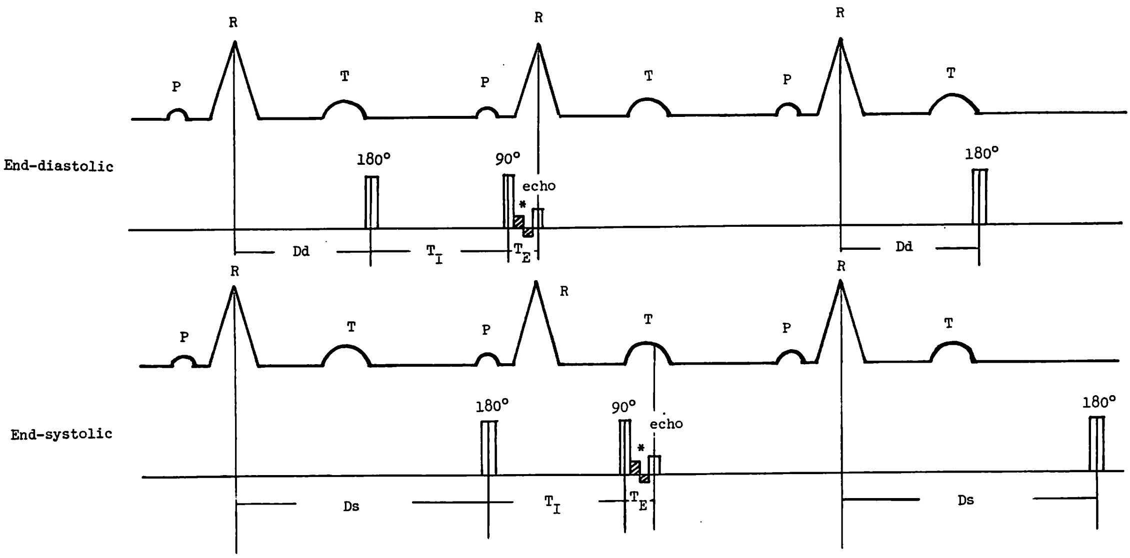

Fig. 1. Pulse sequence of gating in resistive MRI.
The following values are usually applied: $T_I=400$ msec; $T_E=13$ msec.
* = inversion of field gradient; Dd: time delay for diastolic image; Ds: time delay for systolic image.

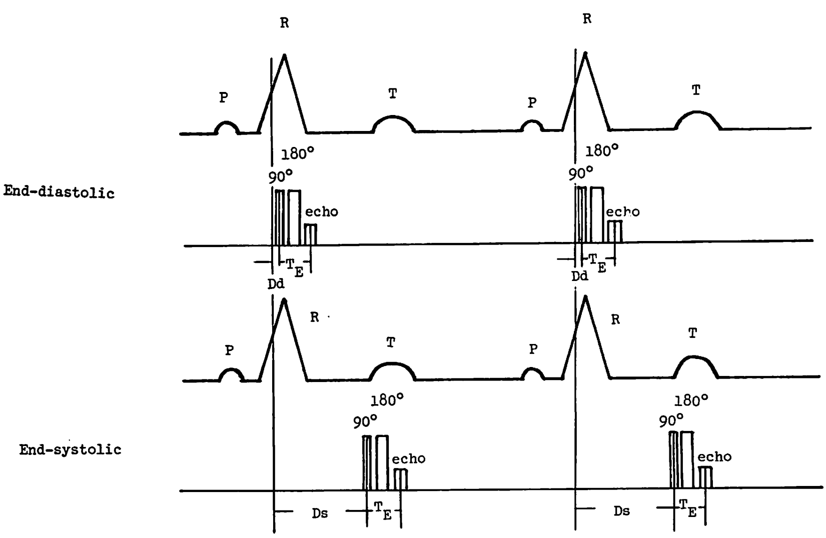

Fig. 2. Pulse sequence of gating in superconductive MRI.
$T_E=35$ and 70 msec.

Table 1. Clinical diagnosis of patients using resistive MRI

Normal	2 (2)
Pericarditis	1 (1)
Cardiomyopathy	4 (2)
Myocardial infarction	12 (7)
Total	19 (12)

The figures in parenthesis indicate the numbers of patients who were evaluated by both MRI and radionuclides techniques.

Table 2. Clinical diagnosis of patients who underwent superconductive MRI

Normal	2 (2)
Cardiomyopathy	2 (1)
Myocardial infarction	10 (5)
Total	14 (8)

by both the first-pass and equilibrium methods using LFOV gamma camera after the injection of 20 mCi of Tc-99m in vivo-labelled erythrocytes. Left ventricular wall motion was measured using both the first-pass and equilibrium images. The left ventricular ejection fraction was also evaluated using both methods, but in this comparative study only the values from the equilibrium method were used.

Patient population

The resistive magnet MR imager was used for 19 patients, 14 were men and five were women, whose ages ranged from 36 to 81 years, with an average age of 54.6 years. There were two normals, four with cardiomyopathy, one with pericarditis, and 12 with myocardial infarction (**Table 1**). Within one week of each other, 12 of the 19 patients were tested using both MRI and radionuclide techniques. Using the superconductive MR imager, 14 patients, 10 men and four women, whose ages ranged from 45 to 72 years and averaged 52.5 years were studied. Eight of the 14 patients were evaluated by both procedures (**Table 2**).

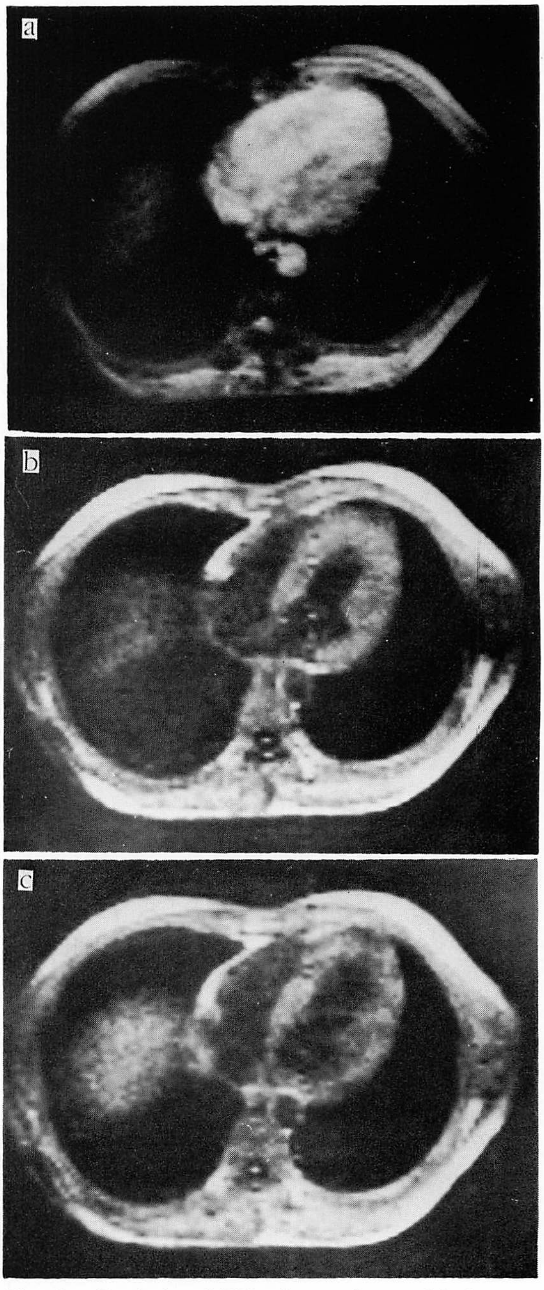

Fig. 3. Resistive MRI of a patient with hypertrophic cardiomyopathy.

In SR image (a), the cardiac muscle cannot be distinguished from the blood pool, probably due to short T_E. End-diastolic (b) and the end-systolic (c) IR images show thickened cardiac muscle and good wall motion of the left ventricle.

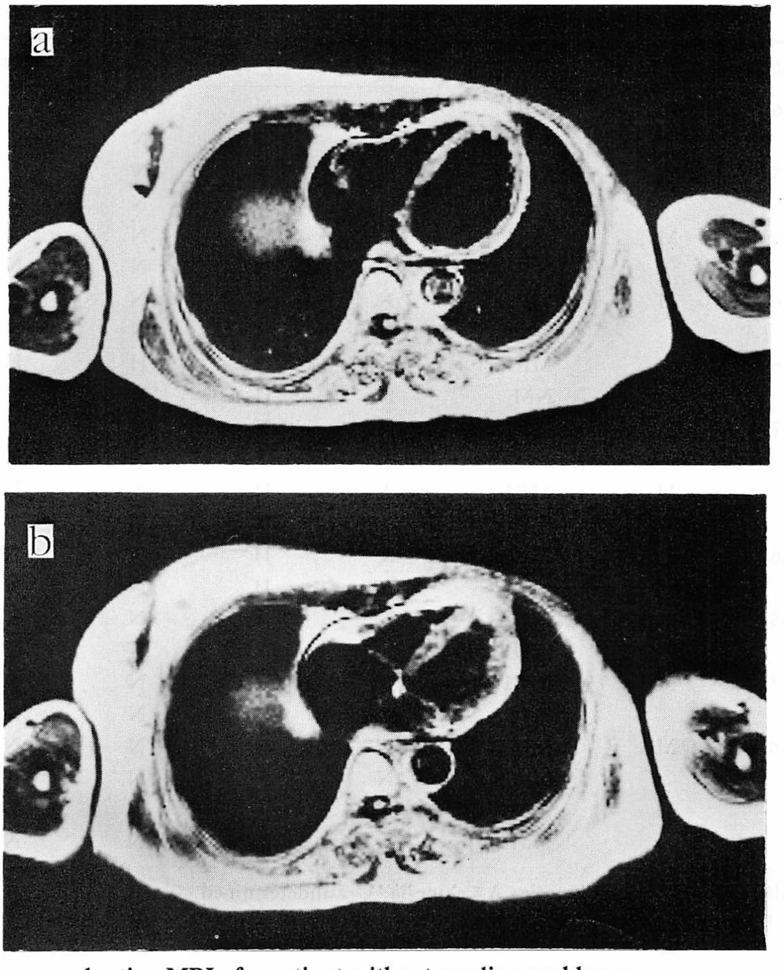

Fig. 4. Superconductive MRI of a patient without cardiac problems.
End-diastolic (a) and end-systolic (b) spin-echo (SE) images reveal good wall motion of the left ventricle. The quality of images is better than that of resistive images shown in Fig. 3.

Results

By resistive magnet (MR) imaging, only the inversion recovery images could distinguish cardiac muscle from the blood pool without using contrast material (**Fig. 3**). Using superconductive MR imaging, all spin-echo images clearly differentiated cardiac muscle from the blood pool. The quality of the images obtained by the superconductive MRI apparatus was superior to that obtained by the resistive magnet imager, largely because of better spatial and contrast resolution, as shown in **Fig. 4**.

The comparative results of left ventricular wall motion assessed by resistive MRI and by gated blood pool images are shown in **Table 3**; those by superconductive MRI and radionuclides, in **Table 4**. Correlations of both modalities with cardiovascular radionuclide techniques were satisfactory except in the inferior wall, which was better evaluated using radionuclide techniques.

Left ventricular ejection fractions obtained by MRI and radionuclide studies are summarized

Table 3. Left ventricular wall motion assessed by resistive magnet MRI

Case	Age	Sex		Anterior	Septum	Lateral	Posterior	Inferior
1.	46	F	MRI	N	N	N	N	U
			NM	N	N	N	N	N
2.	45	M	MRI	N	N	N	N	U
			NM	N	N	N	N	N
3.	49	M	MRI	N	N	N	N	U
			NM	N	N	N	N	N
4.	36	M	MRI	N	N	N	N	U
			NM	N	N	N	N	N
5.	66	F	MRI	H	H	H	H	U
			NM	H	H	H	H	H
6.	47	M	MRI	N	N	N	N	U
			NM	N	N	N	N	H
7.	56	M	MRI	A	H	N	N	U
			NM	A	H	N	N	A
8.	66	F	MRI	A	H	N	N	U
			NM	A	H	N	N	H
9.	45	M	MRI	N	A	N	A	U
			NM	N	A	N	A	A
10.	37	M	MRI	N	H	N	N	U
			NM	N	H	N	N	H
11.	68	M	MRI	N	H	N	N	U
			NM	N	H	N	N	N
12.	56	M	MRI	A	A	N	N	U
			NM	A	H	N	N	A

N=normal wall motion; H=hypokinesia; A=akinesia; U=undetermined.
NM=radionuclide studies.

in **Tables 5 & 6**. Ejection fractions obtained by MRI were moderately lower as compared with those obtained by radionuclide techniques. Correlation of the two methods was good: r=0.84 (resistive) and r=0.85 (superconductive).

Discussion

The phenomenon of nuclear magnetic resonance (NMR), first discovered by Purcell and Block in 1946[1,2], occurs when nuclei having magnetic components are placed in strong magnetic fields. When these magnetized nuclei are exposed to radio waves of a specific frequency, they emit signals having the same frequency as that induced. With NMR phenomenon, information concerning chemical shifts and relaxation times can be obtained. " Chemical shift " refers to the fact that the same nucleus has different resonance conditions in different chemical environments. With chemical shift as the basis for NMR spectroscopy, the structures of individual chemical species can be analyzed noninvasively. NMR spectroscopy has been widely applied to chemistry, especially to structural organic chemistry since 1960.

After stimulation, the nuclei lose energy, emit radio waves, and transfer energy to surrounding molecules while returning to equilibrium. This process by which energy is lost is called " relaxation." These processes are exponential in time and are characterized by two time constants: T_1 (the longitudinal magnetic

Table 4. Left ventricular motion assessed by superconductive magnet MRI

Case	Age	Sex		Anterior	Septum	Lateral	Posterior	Inferior
1.	54	F	MRI	N	N	N	N	U
			NM	N	N	N	N	N
2.	50	F	MRI	N	N	N	N	U
			NM	N	N	N	N	N
3.	50	F	MRI	N	N	N	N	U
			NM	N	N	N	N	N
4.	72	M	MRI	N	N	N	N	U
			NM	N	N	N	N	N
5.	46	M	MRI	N	N	N	N	U
			NM	N	N	N	H	N
6.	62	M	MRI	N	N	N	N	U
			NM	N	N	N	N	A
7.	45	M	MRI	N	N	N	A	U
			NM	N	N	N	A	A
8.	68	M	MRI	A	A	H	N	U
			NM	A	A	H	N	N

N=normal wall motion; H=hypokinesis; A=akinesis; U=undetermined.

Table 5. Left ventricular ejection fraction calculated by resistive magnet MRI

Case	Diagnosis	MRI	NM
1.	Nl	42.9 (%)	59.6 (%)
2.	Nl	37.7	50.9
3.	PC	25.0	50.3
4.	CM	39.3	56.6
5.	CM	17.8	31.1
6.	MI	37.5	55.3
7.	MI	23.1	29.5
8.	MI	32.3	37.7
9.	MI	44.1	48.7
10.	MI	14.6	24.7
11.	MI	31.9	32.0
12.	MI	16.3	23.0

Nl=normal; PC=pericarditis; CM=cardiomyopathy; MI=myocardial infarction.

Table 6. Left ventricular ejection fraction calculated by superconductive magnet MRI

Case	Diagnosis	MRI	NM
1.	Nl	43.1 (%)	53.9 (%)
2.	Nl	65.9	61.9
3.	CM	63.8	87.1
4.	MI	52.1	62.8
5.	MI	46.5	55.8
6.	MI	55.6	46.2
7.	MI	35.3	47.3
8.	MI	11.0	18.6

Nl=normal; CM=cardiomyopathy; MI=myocardial infarction.

relaxation time) and T_2 (the transverse magnetic relaxation time). In 1971, Damadian demonstrated that the T_1 and T_2 relaxation times of malignant lesions differed from those of normal tissues[3]. Damadian and Lauterbur both tried to apply NMR clinically, and Lauterbur reported the successful use of NMR in clinical imaging in 1973[4]. However, only during the past several years has MRI been truly used clinically. This was partly because of the widely successful diagnostic imaging using X-ray CT, which was introduced in 1972[5]. In the 1980s, when the role of CT was clarified, the search for a new

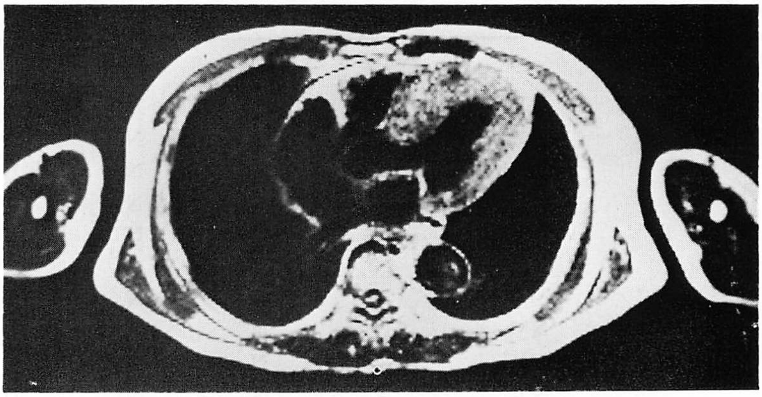

Fig. 5. Gated image of a patient with hypertrophic cardiomyopathy.
End-diastolic MRI shows thickened left ventricular wall, particularly in the septum. The quality of image is better than that of the non-gated one shown in Fig. 6.

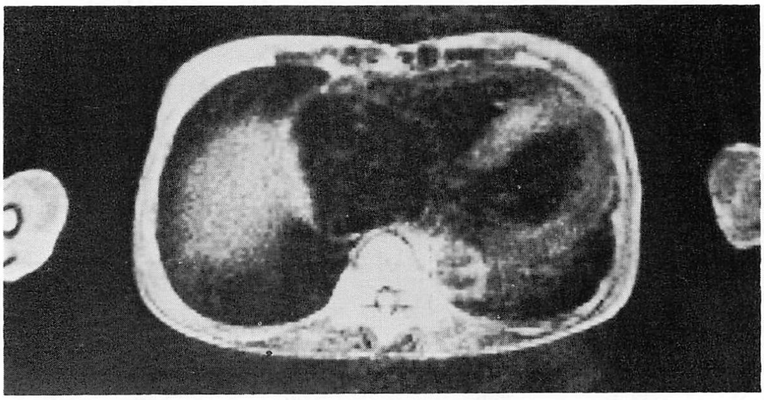

Fig. 6. Non-gated image of a patient with hypertrophic cardiomyopathy.
The left ventricular wall is thought to be thickened on MRI without gating, but because of poor image quality, a definite determination cannot be made.

and more efficient diagnostic modality has intensified. MRI is well-suited to answer this need.

MRI has been classified according to the permanent and electric current magnets used, and the latter, dividing into resistive and superconductive magnet types. Many manufacturers are presently concentrating on producing superconductive magnets because of their uniform, stable magnetic fields. As shown in **Figs. 3 & 4**, the images produced by superconductive type MR apparatus are superior to those produced by resistive type apparatus. There are numerous reports of the usefulness of MRI, particularly in neurology[6,7], but in other fields, its effectiveness is still being evaluated. MRI has been considered useful for cardiovascular diseases, because it can distinguish flowing blood from solid organs without contrast materials or radionuclides[8,9]. Data acquisition times of conventional MRI apparatus are too long to allow precise cardiac imaging. The gating method is mandatory for evaluating cardiac function and for depicting images of good quality (**Figs. 5 & 6**). For gated MRI, plethysmographic, laser-Doppler and electrocardiographic signals have

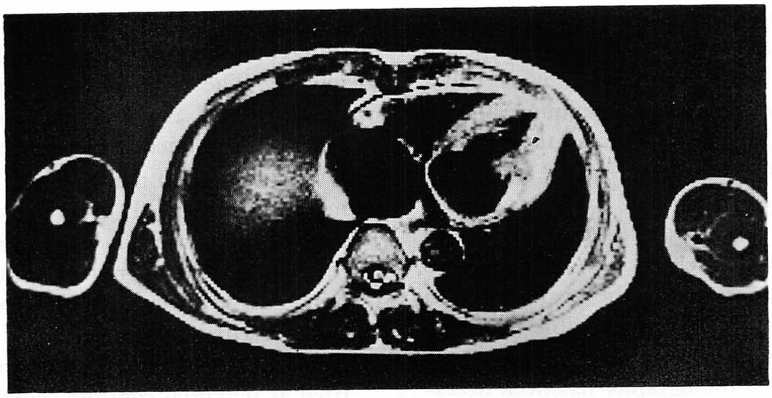

Fig. 7. Image of a patient with old myocardial infarction.
MRI reveals severe thinning of the posterior wall of the left ventricle.

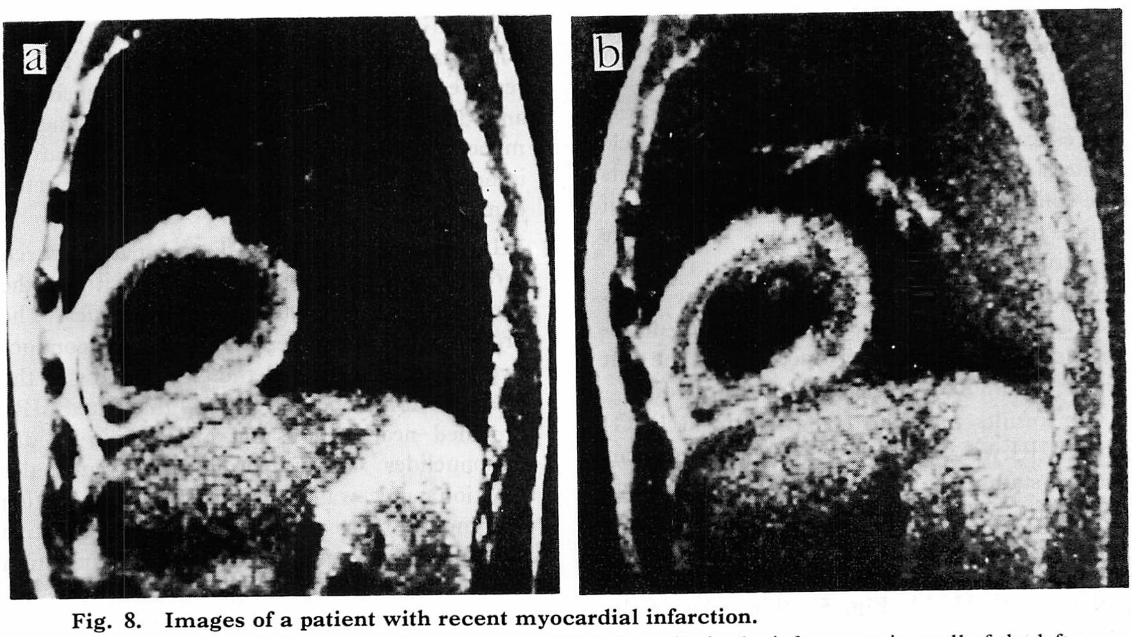

Fig. 8. Images of a patient with recent myocardial infarction.
MRI with T_E of 35 msec. (a) shows an area of high intensity in the inferoposterior wall of the left ventricle. MRI with T_E of 70 msec. (b) reveals an area of higher intensity in the same region, which suggests a prolonged T_2 relaxation time.

been used. The ECG-gating method is reportedly most suitable for in vivo cardiac MRI. The cardiac images from the early portion of the cardiac cycle are difficult to obtain due to intrinsic delays between the R wave of ECG and the peripheral detection of the gating signal by plethysmography and laser-Doppler velocimetry[10].

The R wave of ECG was used as the gating signal in the present study. The purpose of this study was to determine the effectiveness of ECG-gated MRI compared to established cardiovascular radionuclide technology. Using resistive and superconductive MRI and radionuclide techniques, correlations of left ventricular wall motion were the same, except for those of the inferior wall, which were better evaluated by radionuclide technique. This is due to the fact that MRI is limited to transaxial cardiac images in the present study, and the in ferior wall is nearly parallel to this transaxial plane. From end-systole to end-diastole the locus of the inferior wall includes several planes, so inferior wall motion cannot be evaluated in a single plane, even if it were possible to obtain both end-systolic and end-diastolic images in that plane. Sagittal tomography has been necessary to evaluate the inferior cardiac wall by gated MRI. We are now able to evaluate the inferior wall motion using gated sagittal images produced by superconductive MRI. Left ventricular ejection fractions determined by MRI were relatively lower than those by radionuclide technique, because we are currently using only transaxial images, causing the long axis of the left ventricle as measured by MRI to appear shorter than its true long axis. Despite this, the correlation of values by both modalities was satisfactory (resistive: $r=0.85$; superconductive: $r=0.84$). This leads us to believe that use of a new tomographic plane of the heart would permit determining the true ejection fractions of the left ventricle without the need of contrast media.

Our results mentioned above proved ECG-gated MRI was effective in evaluating left ventricular status. We subsequently applied superconductive MRI to myocardial infarction (MI) and hypertrophic cardiomyopathy (HCM). MRI demonstrated diffusely thickened myocardium in patients with HCM (**Fig. 5**), thin areas of the ventricular wall due to old MI (**Fig. 7**), and recent MI with the myocardium of apparently normal thickness. Interestingly, recent MI lesions were represented as areas of prolonged T_2 relaxation times (**Fig. 8**). These results correlated well with previous reports that experimental myocardial infarction in dogs had prolonged T_1 and T_2 values[11~13].

One of the advantages of MRI is its good contrast resolution of soft tissue without the need for contrast materials. However, a suitable contrast material might permit subtle imaging differences between lesions and normal cardiac muscle. The bivalent manganese ion (Mn^{2+}) was first used as a potential pharmaceutical for MRI of experimental myocardial infarction.

Brady reported that nine of 12 dogs receiving manganese showed differences in the image intensities between the normal myocardium and that subjected to reduced perfusion for 90 minutes[14]. However, Mn^{2+} can be toxic to the cardiovascular system. Among many rare-earth materials, metal cations and nitroxide spin labels tried as potential contrast agents for MRI, only Gd-DTPA has been used clinically as an effective contrast agent in patients with cerebral, hepatic and urinary bladder tumors[15], but there has been no report of its application to patients with cardiovascular diseases. Gd-DTPA is reportedly useful in increasing the sensitivity and diagnostic utility of MRI in experimental myocardial infarction and acute myocardial ischemia[16]. Hence, good results can be expected clinically.

In summary, MRI can discriminate between cardiac muscle and vascular walls without the need for contrast media or radionuclides. The present study using resistive and superconductive MRI demonstrated the effectiveness of the ECG-gated method and showed that gated MRI provided nearly the same information as did radionuclides in evaluating left ventricular function and wall motion. Superconductive imaging is more advantageous than resistive type imaging, because of its fast data acquisition and its high quality images. Our clinical experience with ECG-gated superconductive MRI has been brief, but the three-dimensional morphological information provided in various cardiovascular diseases was excellent. We are now investigating the relationship of T_2 relaxation times to heart diseases. With the further development of MRI, improved data analysis, and proper contrast materials, gated MRI will no doubt provide more useful information for the diagnosis of various cardiovascular diseases and become a more effective means of contributing various aspects to cardiovascular evaluations.

心電図同期核磁気共鳴画像の心疾患における有効性の評価

東京大学医学部　放射線医学
*同　　　　　第二内科
西川潤一，大嶽　達，町田喜久雄
飯尾正宏，吉本信雄*，杉本恒明*

要　　約

MRI (核磁気共鳴画像) では，ヨード造影剤や放射性同位元素を用いることなく，非侵襲的に流血と血管壁・心筋とが区別できるので，循環器領域の画像診断法として注目されている．しかしながら，MRI のデータ採取時間は長く，心臓の明瞭な画像を得るためには，心電図同期法の併用が必須である．

我々は心電図同期 MRI の信頼性を確認するために，本法と核医学検査との比較を行った．装置は常電導電磁石 (0.15 Tesla) と超電導電磁石 (0.35 Tesla) を使用した二装置である．症例は常電導 MRI が 12 例，超電導 MRI が 8 例である．

両装置の MRI で，流血と心筋とが明瞭に区別できた．MRI の画質に関しては，超電導 MRI が常電導と比較して優っていた．MRI と核医学検査との比較は，左心室の壁運動と駆出分画指標について行った．左心室の壁運動に関して，両者の相関は，下壁以外は良好であった．左心室の駆出分画指標に関しては，MRI では全般的に低値を示したが，相関係数は常電導 MRI が 0.84，超電導 MRI が 0.85 と，良い相関を示した．

このように，心電図同期 MRI は，非侵襲的に心臓の解剖学的情報に加え，核医学検査に匹敵する動態の情報を提供できるので，これから，心疾患の有用な検査法となると思われる．

文　献

1) Purcell EM, Torrey HC, Pound RV: Resonance absorption by nuclear magnetic moments in a solid. Physiol Rev **69**: 127, 1946
2) Bloch F: Nuclear induction. Physiol Rev **70**: 460–473, 1946
3) Damadian R: Tumor detection by NMR. Science **171**: 1151–1153, 1971
4) Lauterbur PC: Image formation by induced local interactions: Examples employing nuclear magnetic resonance. Nature **242**: 190–191, 1973
5) Ambrose J, Hounsfield G: Computerized transverse axial tomography. Br J Radiol **46**: 148, 1973
6) Bydder GM, Steiner RE, Thomas DJ, Marshall J, Gilderdale DJ, Young IR: Nuclear magnetic resonance imaging of the posterior fossa: 50 cases. Clin Radiol **34**: 173–188, 1983
7) Modic MT, Weinstein MA, Palvlicek W, Starnes DL, Duchesneau PM, Boumphrey F, Hardy RJ: Nuclear magnetic resonance imaging of the spine. Radiology **148**: 757–762, 1983
8) Herfkens RJ, Higgins CB, Hricak H, Lipton MJ, Crooks LE, Lanzer P, Botvinick E, Brundage B, Sheldon PE, Kaufman L: Nuclear magnetic resonance imaging of the cardiovascular system: Normal and pathologic findings. Radiology **147**: 749–759, 1983
9) Axel L, Kressel HY, Thickman D, Epstein DM, Edelstein W, Bottomley P, Redington R, Baum S: NMR imaging of the chest at 0.12T: Initial clinical experience with a resistive magnet. Am J Roentgenol **141**: 1157–1162, 1983
10) Lanzer P, Botvinick EH, Schiller NB, Crooks LE, Arakawa M, Davis PL, Herfkens R, Lipton MJ, Higgins CB: Cardiac imaging using gated magnetic resonance. Radiology **150**: 121–127, 1984
11) Williams ES, Kaplan JI, Thatcher F, Zimmerman G, Knoebel SB: Prolongation of proton spin lattice relaxation times in regionally ischemic tissue from dog hearts. J Nucl Med **21**: 449–453, 1980
12) Higgins CB, Herfkens R, Lipton MJ, Sheldon P, Kaufman L, Crooks LE: Nuclear magnetic resonance imaging of acute myocardial infarction in dogs: Alternation in magnetic relaxation times. Am J Cardiol **52**: 184–188, 1983
13) Wesbey G, Higgins CB, Lanzer P, Botvinick E, Lipton MJ: Imaging and characterization of acute myocardial infarction in vivo by gated nuclear magnetic resonance. Circulation **69**: 125–130, 1984
14) Brady TJ, Goldman MR, Pykett IL, Buonanno FS, Kistler JP, Newhouse JH, Burt CT, Hinshaw WS, Pohost GM: Proton nuclear magnetic resonance imaging of regionally ischemic canine hearts: Effect of paramagnetic proton signal enhancement. Radiology **144**: 343–347, 1982
15) Carr DH, Brown J, Bydder GM, Steiner RE, Weinmann HJ, Speck U, Hall AS, Young IR:

Gadolinium-DTPA as a contrast agent in MRI: Initial clinical experience in 20 patients. Am J Roentgenol **143**: 215–224, 1984
16) McNamara MT, Higgins CB, Ehman RL, Revel D, Sievers R, Brasch RC: Acute myocardial ischemia: Magnetic resonance contrast enhancement with Gadolinium-DTPA. Radiology **153**: 157–163, 1984