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Whole-heart 3D Late Gadolinium-enhanced MR Imaging: Investigation of Optimal Scan Parameters and Clinical Usefulness

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Purpose: Whole-heart 3-dimensional (3D) late-gadolinium-enhanced magnetic resonance (MR) imaging (WH-LGE) uses respiratory gating combined with acquisition of 3D data for the entire heart in a single scan, which permits reconstruction of any plane with high resolution. We investigated the optimal scan parameters and compared WH-LGE with the conventional scanning method.

Materials and Methods: We employed inversion recovery 3D fast field echo using a 1.5-tesla system and scan parameters: repetition time (TR), 6.6 ms; echo time (TE), 2.5 ms; number of segments, 2; parallel imaging factor, 1.8; matrix size, 128 × 256; field of view (FOV), 320 × 320 mm; and acquisition slice thickness, 3 mm (reconstruction slice thickness, 1.5 mm). Five healthy volunteers underwent scanning during free breathing with real-time motion correction, from which we determined optimal scan parameters. We then used those parameters to scan 25 patients with myocardial infarction to compare scan time and image quality between the WH-LGE and conventional 3D breath-holding methods (slice thickness, 10 mm; matrix size, 128 × 256).

Results: Results in volunteers showed optimal scan parameters of 12° flip angle, fat suppression turned off in combination, and interleaved ordering. In clinical cases, scan times did not differ significantly. Sharpness of the margins of normal myocardium at the apex of the heart and contrast between enhanced and nonenhanced myocardium improved significantly with WH-LGE.

Conclusion: WH-LGE yields high resolution images during free breathing and is considered useful for accurately estimating the area and transmural extent of myocardial infarction.

Keywords: *cardiac, LGE, MRI, myocardial infarction, whole-heart method*

Introduction

Many studies have reported the usefulness of late gadolinium-enhanced (LGE) magnetic resonance (MR) imaging for assessing the viability and prognosis of infarcted myocardium because it permits clear visualization of infarcted myocardium.^{1–14} Three-dimensional (3D) scanning is the current trend in LGE MR imaging because it enables acquisition of data for the entire heart in a short time. However, the current 3D scan method (conventional method) permits data acquisition in only a single

direction during one breath-hold, so patients must be instructed to hold their breath several times for acquisition in multiple directions. This may cause discomfort in patients with myocardial infarction and make imaging challenging if patients cannot hold their breath properly. Insufficient in-plane resolution and resolution in slice direction also make precise evaluation of the extent and depth of infarction difficult using the conventional method.

Given this background, we have developed the whole-heart 3D LGE MR imaging (WH-LGE) method, which permits acquisition of 3D data for the entire heart in a single scan during quiet breathing using high precision real-time motion correction (RMC) respiratory gating. In the WH-LGE

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method, any desired plane can be observed by reconstructing the image data acquired in a single scan with high resolution maintained in all planes. We performed basic assessment of this new method and clinical assessment focusing on comparison with the conventional method.

Materials and Methods

Using a 1.5-tesla MR imaging system (EXCELART Vantage™ powered by Atlas, Toshiba Medical Systems Corporation, Japan) and 16-channel body coil (Atlas SPEEDER, Toshiba), we acquired images using an inversion recovery 3D fast field echo (IR-3D-FFE) technique with parameters shown in Table 1. Figure 1 shows original images acquired using the WH-LGE method and images generated by multiplanar reconstruction (MPR). We assessed the WH-LGE method with regard to the items described below.

Assessment of optimal scan parameters

Five healthy volunteers (4 men, one woman, aged 25 to 53 years, average age 38.6 years) underwent scanning without gadolinium (Gd) contrast

agent and with 12 combinations of scan parameters: flip angle (10°, 12°, or 14°), fat suppression (on or off), and data acquisition order (sequential or interleaved). All volunteers provided written informed consent. The images obtained were evalu-

Table 1. Imaging parameters for the whole-heart 3-dimensional late gadolinium-enhanced magnetic resonance imaging (WH-LGE) and conventional methods

Parameter	WH-LGE	Conventional
Repetition time (ms)	6.6	5.0
Echo time (ms)	2.5	2.0
Number of segments	2	2
Parallel imaging factor	1.8	2.0
Matrix	128 × 256	128 × 256
Field of view (mm)	320 × 320	350 × 350
Slice thickness (mm)	3	10
Reconstruction slice thickness (mm)	1.5	
Slab thickness	90	100
Threshold value width for Real-time motion correction (mm)	5

Fig. 1. Whole-heart 3-dimensional late gadolinium-enhanced magnetic resonance imaging (WH-LGE). **a.** Twenty-one consecutive reconstructed images of all 60 data acquired using WH-LGE in the transverse plane perpendicular to the body axis show late enhancement of the infarcted region in the inferior wall. **b–d.** Multiplanar reconstructed (MPR) images generated from the whole-heart data in (a). **b:** short-axis view **c:** long-axis view **d:** 4-chamber view

ated visually and quantitatively.

Two radiologists specializing in cardiac MR imaging and with experience interpreting cardiac MR images assessed the images with regard to respiratory motion, uniformity of left ventricular myocardial signal intensity, and sharpness of left ventricular myocardial margins. They graded each characteristic on a 4-point scale. For artifacts from respiratory motion (chest wall), they used scores of: 0, very noticeable (substantial effect on diagnosis); 1, noticeable (minor effect on diagnosis); 2, slight (no effect on diagnosis); and 3, none. For uniformity of left ventricular myocardial signal intensity, they assigned scores of: 0, very nonuniform; 1, nonuniform; 2, slightly nonuniform; and 3, uniform. They scored sharpness of left ventricular myocardial margins using: 0, totally unclear; 1, mostly unclear; 2, partially unclear; and 3, clear. The two resolved any discordant assessment by discussion and consensus. Comparison was based on the total point scores for each image.

We measured signal intensity in 12 regions of interest (ROIs) we set in the left ventricular myocardium (Fig. 2). We chose 3 slice images (one slice was upper, a second slice was middle, and the third slice was lower) for measurement based on reconstructed images acquired using WH-LGE images in the transverse plane. We analyzed measurements statistically using the F-test to identify significant differences in covariance in the signal intensity values for the different scan parameters.

Assessment based on clinical cases

Based on the results of the above assessments, patients underwent scanning using the WH-LGE and conventional methods to evaluate myocardial infarction, and we compared actual scan time and image quality between the 2 methods. The subjects were 25 patients (19 men, 6 women; aged 38 to 81 years, average age 65.4 years) with known or sus-

pected myocardial infarction who underwent MR imaging examination at our facility between March 1st and October 31st 2009. The institutional review board of our hospital approved this study protocol and all patients provided written informed consent. Table 1 delineates the scan parameters for the conventional method. In the conventional method, the flip angle was set to 12° , and the inversion time (TI) to a value between 250 and 280 ms based on the R-R intervals for electrocardiographic (ECG) gating and the results obtained by TI-Prep scan (the method for TI optimization). The injection volume of Gd contrast agent was 0.2 mL/kg. Data acquisition using the conventional method was started 13 min after the start of injection, and acquisition using the WH-LGE method was started 16 min after the start of injection.

Scan time was defined as the period from the start to end of data acquisition for the WH-LGE method and from the start of data acquisition to the completion of acquisition of the left ventricular short-axis, left ventricular long-axis, and 4-chamber cross-sectional images (the entire period, including breath-holds and pauses between breath-holds) for the conventional method.

We also assessed visually and quantitatively. Two radiologists specializing in cardiac MR imaging and with experience interpreting cardiac MR images assessed the acquired images with regard to sharpness of the margins of normal myocardium at the base and apex of the heart and respiratory motion (chest wall) artifacts at the base and apex of the heart. We also compared sharpness of the border between infarcted (enhanced) and adjacent normal (nonenhanced) myocardium regardless of sub-endocardial or transmural enhancement pattern, and we compared contrast between infarcted (enhanced) and adjacent normal (nonenhanced) myocardium by segments according to American Heart Association (AHA) classification. The 2 radiolo-

Fig. 2. Schema for quantitative measurement of myocardial signal intensity in the left ventricle based on acquired reconstructed images using whole-heart 3-dimensional late gadolinium-enhanced magnetic resonance imaging (WH-LGE) in the transverse plane. region of interest (ROI): 16 to 18 mm²; a: upper level; b: middle level; c: lower level

gists resolved any discordant assessment by discussion and consensus.

We used the *t*-test to identify significant differences between the groups of data acquired using the WH-LGE and conventional methods (Fig. 3) and to measure the contrast ratio (CR) between infarcted (enhanced) and normal (nonenhanced) myocardium. We set 3 ROIs arbitrarily in the infarcted lesion and normal myocardium, in which we measured signal intensity, calculated the average of these values, and used the *t*-test for statistical analysis to identify significant differences.

Results

Assessment of optimal scan parameters in healthy volunteers

Table 2 delineates the results of visual assessment, which suggest that the optimal combination of scan parameters is a flip angle of 12°, fat suppression turned off, and interleaved ordering. Table 3 shows the results of quantitative measurement. No significant differences were observed in the average of covariance values for the myocardial

Table 2. Visual assessment of optimal scan parameters in 5 healthy volunteers

Combinations of scan parameters	a	b	c	Total
1 FA 10°, f/s off, Seq	1.8	1.8	1.8	5.4
2 FA 10°, f/s on, Seq	1.6	1.2	1.2	4
3 FA 12°, f/s off, Seq	2	1.6	1.2	4.8
4 FA 12°, f/s on, Seq	1.8	1.2	1.6	4.6
5 FA 14°, f/s off, Seq	1.4	1.2	1	3.6
6 FA 14°, f/s on, Seq	1	0.8	1.2	3
7 FA 10°, f/s off, Int	1	1.8	1.8	4.6
8 FA 10°, f/s on, Int	2	0.6	1.8	4.4
9 FA 12°, f/s off, Int	1.2	2.4	2.6	6.2
10 FA 12°, f/s on, Int	1.2	0.8	2	4
11 FA 14°, f/s off, Int	1	2.2	2.4	5.6
12 FA 14°, f/s on, Int	1.2	1.2	2	4.4

a: respiratory motion artifacts; b: uniformity of left ventricular myocardial signal intensity; c: sharpness of left ventricular myocardial margins; FA: flip angle; f/s: fat suppression, Seq: sequential ordering; Int: interleaved ordering

Fig. 3. Images acquired using the whole-heart 3-dimensional late gadolinium-enhanced magnetic resonance imaging (WH-LGE) method (multiplanar reconstruction [MPR] images (a, b) and the conventional method (c, d) in the same patient. a, c: base of the heart; b, d: apex of the heart

Table 3. Quantitative measurement of myocardial signal intensity in the left ventricle in 5 healthy volunteers

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Average of covariance values
1	301.2 ± 94.8	241.4 ± 69.3	344.9 ± 112.9	299.3 ± 107.1	316.5 ± 101.1	97.0
2	322.1 ± 105.1	323.1 ± 108.9	526.7 ± 140.5	465.0 ± 173.1	337.6 ± 107.4	127.0
3	324.3 ± 113.7	337.4 ± 136.3	370.7 ± 145.3	269.5 ± 115.1	273.1 ± 73.4	116.7
4	378.9 ± 167.7	514.9 ± 317.9	344.9 ± 63.4	382.6 ± 95.4	345.5 ± 135.2	155.9
5	371.6 ± 87.6	356.1 ± 234.1	361.8 ± 126.8	254.5 ± 84.5	378.5 ± 150.1	136.6
6	525.0 ± 187.2	395.4 ± 219.0	376.7 ± 168.6	323.5 ± 96.9	384.6 ± 206.2	175.6
7	315.2 ± 76.8	295.7 ± 104.7	350.9 ± 112.2	348.4 ± 131.3	347.1 ± 129.8	111.0
8	543.8 ± 168.4	371.6 ± 170.8	436.5 ± 158.2	401.5 ± 173.1	370.7 ± 152.5	164.6
9	299.5 ± 119.1	338.9 ± 216.3	306.1 ± 86.5	379.4 ± 161.0	312.7 ± 130.4	142.6
10	691.1 ± 250.8	500.1 ± 262.8	563.5 ± 251.2	377.5 ± 154.6	410.9 ± 183.8	220.6
11	354.0 ± 135.3	287.8 ± 186.1	297.0 ± 83.4	300.7 ± 162.6	322.6 ± 133.1	140.1
12	674.3 ± 197.1	440.0 ± 197.7	721.2 ± 183.3	308.4 ± 116.0	521.2 ± 316.5	202.1

1~12: Combinations of scan parameters

Table 4. The results for scan time measurement and the detection rate of real-time motion correction

	Scan time	Average of scan time
WH-LGE	1 min 40 s ~ 4 min 30 s	3 min 2 s
(Detection rate of RMC)	(69% ~ 31%)	(52%)
Conventional method	2 min 16 s ~ 2 min 40 s	2 min 23 s

RMC: real-time motion correction; WH-LGE: whole-heart 3-dimensional late gadolinium-enhanced magnetic resonance imaging

signal intensities.

Assessment based on clinical cases

We observed LGE in 24 of the 25 patients and 116 segments classified according to the AHA classification. Of these, 40 segments showed subendocardial enhancement that extended less than half-way through the entire thickness of the myocardium, and 76 segments showed transmural enhancement of 50% or greater.

Table 4 shows the results for scan time measurement and the detection rate of real-time motion correction. Scan time tended to be longer as the detection rate decreased. Although the average scanning time was slightly longer using the WH-LGE method than the conventional method, the *t*-test identified no significant difference ($P = 0.092$).

Figure 4 shows the results of visual assessment, which suggest the significant superiority of WH-LGE to the conventional method with regard to sharpness of the margins of normal myocardium at the apex of the heart ($P < 0.05$) and contrast between infarcted (enhanced) and adjacent normal (nonenhanced) myocardium ($P < 0.01$) and of the

conventional method to WH-LGE with regard to sharpness of the margins of normal myocardium and respiratory motion (chest wall) artifacts at the base of the heart ($P < 0.05$). No significant differences were observed in respiratory motion (chest wall) artifacts at the apex of the heart and in sharpness of the border between infarcted (enhanced) and adjacent normal (nonenhanced) myocardium.

Contrast ratio analysis showed no significant difference between WH-LGE (12.53 ± 2.80) and the conventional method (11.06 ± 2.35) ($P = 0.109$).

Discussion

We investigated the optimal parameters for examinations and clinical usefulness of the WH-LGE method we developed to acquire 3D data for the entire heart in a single scan during quiet breathing using high precision real-time motion correction respiratory gating.

In myocardial LGE MR imaging, scanning is started 10 to 20 min after intravenous injection of Gd-DTPA contrast agent.¹⁵ This method can depict myocardial lesions with high reproducibility and

Fig. 4. Comparison of image quality between the whole-heart 3-dimensional late gadolinium-enhanced magnetic resonance imaging (WH-LGE) method and the conventional method in 25 patients with myocardial infarction. **a:** sharpness of the margins of normal myocardium at the base of the heart; **b:** sharpness of the margins of normal myocardium at the apex of the heart; **c:** respiratory motion (chest wall) artifacts at the base of the heart; **d:** respiratory motion (chest wall) artifacts at the apex of the heart; **e:** sharpness of the border between infarcted (enhanced) and adjacent normal (nonenhanced) myocardium; **f:** contrast between infarcted (enhanced) and adjacent normal (nonenhanced) myocardium. * $P < 0.01$; ** $P < 0.05$; NS: no significant difference

has recently been applied to various diseases, particularly ischemic heart disease.^{16–19} Kim and associates have reported that recovery of myocardial function can decrease as the transmural depth of the enhanced myocardial tissues increases.²⁰ Therefore, accurate assessment of the extent and depth of the enhanced region is important in assessing prognosis.

Recently, the introduction of ECG-gated scan with breath-holding and development of the inversion recovery (IR) technique have dramatically improved contrast between infarcted and normal myocardium. Furthermore, the development of the 3D data acquisition technique combined with parallel imaging markedly reduced scan time and enabled data acquisition for the entire heart in a single scan.⁹ Prior to that, only 2-dimensional (2D) data acquisition was possible, and only a single plane could be acquired in a single scan. However, the large slice thickness required for the 3D technique diminishes image sharpness, a disadvantage in assessing the extent and depth of infarcted myocardial tissues. In addition, imaging with the 3D technique requires scanning several times for different planes (including the short-axis, long-axis, and 4-chamber cross-sectional planes), and patients must hold their breath for each scan. This may be difficult for patients with ischemic heart disease and those who cannot hold their breath properly.

In this study, we assessed the optimal scan parameters in healthy volunteers and achieved the highest score for visual assessment by combining a flip angle of 12° with fat suppression turned off and interleaved ordering. Because interleaved ordering is inherently unaffected by motion, this method seems more suitable to scanning during quiet breathing. In the quantitative assessment of signal intensity uniformity in the left ventricular myocardium, we observed no significant differences among the various combinations of parameters.

Use of the WH-LGE method permits acquisition of 3D data for the entire heart in a single scan and viewing of any desired plane of the heart (including the short- and long-axis planes) by reconstruction of the acquired 3D data (Fig. 1). In the clinical cases, the visual scores of the WH-LGE method were significantly higher than those for the conventional method with regard to sharpness of normal myocardium at the apex of the heart and contrast between the enhanced region and normal myocardium. In the conventional method, use of a 10-mm slice thickness resulted in image blurring (reduced sharpness) due to partial volume effects, especially at the apex of the heart. In the WH-LGE method, on the other hand, a high resolution of 3 mm or less could be maintained in all planes. Although the difference was not significant, the sharpness of the border between infarcted and nor-

mal myocardium was better with the WH-LGE method than the conventional method ($P=0.056$). Based on these factors, it can be expected that this advantage should permit more accurate assessment of the extent and depth of infarcted myocardial tissue.

The WH-LGE method was judged to be inferior to the conventional method in visual assessment of the sharpness of normal myocardium and respiratory motion artifacts at the base of the heart. We assume this is attributable to respiratory motion artifacts from the chest wall overlapping the base of the heart and can therefore be overcome by adjusting the field of view.

We did not directly compare regions of enhancement and pathological specimens of infarcted tissues and so cannot assess their correspondence. However, in an animal study, Kim and associates² reported close agreement between the region of enhancement in MR images and the extent of infarcted tissue (region of ischemic necrosis) in pathological specimens.² We believe, then, that we can assume such close correspondence in the present study.

In scanning using the WH-LGE method, acquisition of data in a plane perpendicular to the body axis eliminates the need to perform complicated procedures for positioning the scanning plane. Furthermore, because the method can be performed easily with little influence by the skill of the technologist performing the study, reduced examination time can be expected. The slightly longer scan time for the WH-LGE method than the conventional method (based on actual measurements) can be explained by the time needed to compensate for the lower detection rate of RMC for patients with an unstable breathing pattern. Therefore, examination time could be reduced and data acquisition efficiency improved by instructing the patient to take shallow breaths or by applying an abdominal band.

Coronary MR angiography (MRA), in which coronary lesions are visualized directly, is one MR imaging method used to diagnose ischemic heart disease, and whole-heart 3D coronary MRA is the current preferred method.²¹ The plane setting procedure is similar in this method and the WH-LGE method, so scanning may be relatively easy using both these methods sequentially. It is expected that, in the future, it should be possible to generate images that combine data acquired using the WH-LGE method and whole-heart 3D coronary MRA and that the fused images can be used to evaluate the relationships between stenotic lesions and the extent of infarcted myocardium.

There are several limitations in our study. First, we cannot prove precisely the actual extent of infarcted myocardial tissues because we cannot perform pathological examinations. Second, the number of patients in our study is small, and further study with a larger study population is needed. Third, based on our assessment of optimal scan parameters, we performed examinations in clinical cases without fat suppression; this parameter may have limited clinical use in some cases, such as diseases of right ventricular myocardium or pericardium.

Conclusion

Whole-heart 3D late gadolinium-enhanced MR imaging can be used to acquire high-resolution images during free breathing and can be useful for accurately estimating the area and transmural extent of myocardial infarction.

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