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Feasibility of free-breathing late gadolinium-enhanced cardiovascular MRI for assessment of myocardial infarction: Navigator-gated versus single-shot imaging

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ABSTRACT

Objectives: The aim of this study was to evaluate the feasibility of two free-breathing late gadolinium-enhanced cardiovascular magnetic resonance (LGE-CMR) techniques (two-dimensional segmented navigator-gated [NAV-LGE] and single-shot [SS-LGE]) by comparing with breath-hold LGE-CMR (BH-LGE) as reference.
Methods: A total of 200 consecutive patients underwent the three LGE-CMR imaging techniques. BH patterns were assessed with dynamic navigator MR imaging. Image quality was graded on a 5-point scale (4 = optimal; 0 = not assessable). In patients with sufficient BH capability (diaphragmatic movement with a deviation of <3 mm), hyperenhancement was scored with a 5-point scale, and global infarct size (%left ventricle) was quantified.
Results: Compared to free-breathing LGE-CMR, BH-LGE had higher image quality grade in patients with sufficient BH capability ($P<0.01$ [vs. NAV-LGE]; $P<0.001$ [vs. SS-LGE]) but poorer image quality in patients with insufficient BH capability ($P<0.001$ [vs. NAV-LGE]; $P<0.01$ [vs. SS-LGE]). NAV-LGE had higher sensitivity for infarct detection than SS-LGE (97.1% vs. 88.4%, $P<0.05$), but specificity was not significantly different (97.3% vs. 94.7%, $P=0.37$). By Bland–Altman analysis, the average differences in global infarct size were 0.4% and 1.2%, and the limits of agreement were ± 4.0% and ± 5.9% for NAV- and SS-LGE, respectively.
Conclusions: Although both NAV- and SS-LGE improve the image quality in patients with insufficient BH capability, NAV-LGE is superior to SS-LGE in infarct detection and infarct size measurement. NAV-LGE can be a possible first-line technique for patients with inability to perform sufficient BH.

1. Introduction

Recognition of myocardial infarction (MI) plays an important role in patients' risk stratification and management [1]. Late gadolinium-enhanced cardiovascular magnetic resonance (LGE-CMR) imaging has been well established for visualization of MI and assessment of myocardial viability in patients with ischemic heart disease [2,3]. Breath-hold (BH) LGE-CMR (BH-LGE) using inversion-recovery segmented gradient echo sequence has been validated as a standard of reference in animal models and human studies [4]. During BH-LGE, image data are commonly acquired over a period of several heartbeats during suspended respiration in order to minimize artifacts from respiratory motion. However, among patients with coronary artery disease specifically those in the older age group or with concomitant respiratory disease, they often find it difficult to hold their breath due either to dyspnea or simply to poor response to BH instructions. A previous study demonstrated that the diaphragm showed continuous drift during BH in one-third of patients, who are able to BH [5]. This resulted in reduced image quality and diagnostic accuracy of the standard BH-LGE [6].

Single-shot LGE-CMR (SS-LGE) using steady state free-precession sequence has become a practical and widely used procedure in patients who are unable to hold their breath [6,7]. However, SS-LGE poses the disadvantages of failure to identify small subendocardial infarcts and underestimation of infarct size [7]. Recently, respiratory navigator-gated LGE-CMR (NAV-LGE) during free-breathing using diaphragmatic navigator echo has been proposed. This technique can be applied to two-dimensional SS imaging [8], two-dimensional segmented imaging [9,10], or three-dimensional imaging [11,12]. Although

Abbreviations: BH, breath-hold; CMR, cardiovascular magnetic resonance; LGE, late gadolinium-enhanced; LV, left ventricle/ventricular; MI, myocardial infarction; NAV, navigator-gated; SDNR, signal difference-to-noise ratio; SI, signal intensity; SNR, signal-to-noise ratio; SS, single-shot.

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navigator-gated three-dimensional LGE-CMR enables acquisition of a single slab that covers the entire heart without slice misregistration, prolonged imaging time is required for the entire heart and results in incomplete nulling of the normal myocardium. With two-dimensional NAV-LGE, imaging for the entire heart can be divided into several stacks of images so that the contrast agent's washout effects are minimized during each imaging session.

Thus far, limited data that involve a small number of subjects exist as regards the clinical application of two-dimensional segmented NAV-LGE. The aim of this study was to prospectively evaluate the feasibility of the two free-breathing LGE-CMR techniques in a large number of subjects on a widely applicable 1.5-T MR system by comparing with BH-LGE as the standard of reference.

2. Subjects and methods

All imaging studies were clinically indicated for the patients. The study protocol was approved by the local ethics committee, and written informed consent was obtained from all patients before the examination.

2.1. Study populations

This prospective study enrolled 200 consecutive patients (median age, 69 years; interquartile range, 62–76 years) with known or suspected coronary artery disease scheduled to undergo LGE-CMR imaging. Exclusion criteria included acute myocardial infarction, primary myocardial disease, inability to hold a breath during scanning, severe arrhythmia, or any contraindications for contrast-enhanced CMR examination.

2.2. CMR imaging protocol

Imaging was performed on a 1.5-T scanner (MAGNETOM Avanto, Siemens Healthcare) with a 12-channel phased-array coil. The combination of stress–rest perfusion and LGE imaging was performed as described elsewhere [13,14]. Briefly, stress perfusion imaging was performed using a bolus injection of 0.075 mmol/kg gadodiamide (Gd-DTPA-BMA; Omniscan, GE Healthcare). Approximately 10 min after stress perfusion imaging, the scan was repeated during resting conditions using additional 0.075 mmol/kg gadodiamide. Thus, a total dose of 0.15 mmol/kg gadodiamide was administered. LGE imaging was performed at least 5 min after rest perfusion imaging. We obtained short-axis views every 10 mm that cover the whole left ventricle (LV) and long-axis views (two- and four-chamber views) for each technique. Image data were acquired every other heartbeat during middiastole. Inversion time was adjusted in order to null normal myocardium for each technique. Just before LGE imaging, a segmented inversion recovery steady-state free-precession pulse sequence was performed to determine the optimal inversion time [15]. The inversion time was adjusted longer with the time delay between contrast administration and imaging as needed.

2.2.1. BH-LGE

BH-LGE was performed during a breath-hold at end-inspiration using an inversion-recovery segmented gradient echo sequence [3,4]. The acquisition parameters were repetition time/echo time, 8.3 ms/3.9 ms; flip angle, 25°; 25 k-space lines per segment; GRAPPA factor, 2; typical spatial resolution, 2.0×1.4×8 mm; and temporal resolution, 208 ms. With data acquisition every other heartbeat, imaging of one slice was completed during 7 cardiac cycles.

2.2.2. NAV-LGE

NAV-LGE was performed during free-breathing using a navigator echo to monitor the position of the right hemidiaphragm for respiratory gating with the following parameters: repetition time/echo time, 8.3 ms/3.9 ms; flip angle, 25°; 25 k-space lines per segment; GRAPPA factor, 2; typical spatial resolution, 2.0×1.4×8 mm; temporal resolution, 208 ms; gating window, ±4 mm; and correction factor, 0.6 [16]. Image acquisition of NAV-LGE was divided into three sessions, including two stacks of short-axis images and one stack of long-axis images, in order to minimize the contrast agent's washout effects during each session and to adjust the inversion time as appropriate.

2.2.3. SS-LGE

SS-LGE was performed during free-breathing with a single-shot inversion-recovery steady state free-precession sequence. The temporal resolution was matched at the expense of a reduced spatial resolution due to the limited number of k-space lines [7]. The acquisition parameters were repetition time/echo time, 3.1 ms/1.3 ms; flip angle, 40°; 66 k-space lines per segment; GRAPPA factor, 2; typical spatial resolution, 2.4×1.8×8 mm; and temporal resolution, 207 ms.

2.2.4. Order of LGE-CMR techniques

Either BH- or NAV-LGE was performed first followed by SS-LGE. The rest of BH- or NAV-LGE was performed last. Two different orders were used alternately to minimize the influence of interval after administration of gadolinium.

2.2.5. Assessment of BH pattern

Between rest perfusion and LGE imaging, dynamic navigator MR imaging was performed to assess diaphragmatic movement. During navigator MR imaging, patients were asked to hold their breath at end-inspiration for approximately 15 s. The BH pattern was assigned to one of the following patterns as previously described [5]:

1. Steady plateau: The diaphragm was in a steady plateau position throughout breath-hold with a deviation of <3 mm.
2. Initial drift followed by plateau phase: The position of the diaphragm initially drifted and was immediately followed by a plateau phase with a deviation of <3 mm.
3. Continuous drift: The diaphragm exhibited continuous drift to one direction with a deviation of ≥3 mm.
4. Irregular and unsteady: The diaphragm was in a completely irregular and unsteady movement with a deviation of ≥3 mm.

Patterns 1 and 2 were considered as sufficient BH capability.

2.2.6. Acquisition time

The total acquisition time was measured for each technique. The time between breath-holds in BH acquisitions and the time necessary for imaging setup were included.

2.3. Image analysis

Independent randomized blinded off-line image analysis was performed with the use of dedicated software by two experienced observers (H.M. and T.M.). Inter-observer disagreement as regards the grading of LGE and image quality score was resolved with a consensus interpretation.

2.3.1. Image quality

Image quality, with note of sharp delineation of the myocardial border, motion artifacts, and confidence of transmurality, was graded based on a 5-point scale (image quality score: 4 = optimal, no artifacts; 3 = good, minor artifacts; 2 = fair, moderate artifacts but diagnosable; 1 = poor, severe artifacts and barely diagnosable; 0 = not assessable). The most apical section was defined as the first image with a left ventricular (LV) lumen. The most basal section was defined as the first image with an LV outflow or an extension of the LV myocardium with >50% of the circumference. Acceptable image quality for routine clinical diagnostic purposes was considered as image quality score of ≥2.

Quantitative analysis was performed in patients with sufficient BH capability and hyperenhancement in all of the techniques. One short-axis image which typically characterized the infarct was selected for each patient. Regions of interest were placed within infarct, remote myocardium, and LV cavity to measure the mean signal intensity (SI). The SD of background noise (σ) was also measured outside the body. Signal-to-noise ratio (SNR) and signal difference-to-noise ratio (SDNR) were calculated based on the following equations: $SNR_A = SI_A/\sigma$; $SDNR_{A/B} = (SI_A - SI_B)/\sigma$, where SI_A is the mean SI of region A. However, SNR and SDNR should be considered only as approximations in the setting of parallel imaging.

2.3.2. LGE

In patients with sufficient BH patterns, the extent of hyperenhancement was scored on a 17-segment model [17] with a 5-point scale (0, no hyperenhancement; 1, 1–25%; 2, 26–50%; 3, 51–75%; 4, 76–100%) [7]. When hyperenhancement did not cover an entire myocardial segment, a segment with hyperenhancement extending >50% of the circumference was considered hyperenhanced. Global infarct size as a percentage of LV myocardium was calculated by the sum of segments with LGE (each weighted by the midpoint of the range of enhancement for the given segmental score; i.e., 1 = 13%, 2 = 38%, 3 = 63%, 4 = 88%) and divided by 17 [7].

2.4. Power calculation and statistical analysis

The sensitivity/specificity of NAV- and SS-LGE based on previous studies was 98%/100% and 87%/96%, respectively [7,10]. The sample size was based on the hypothesis that NAV-LGE would yield a higher sensitivity than SS-LGE because detection of MI plays an

Table 1
Visual analysis of image quality.

Breath-hold pattern	Breath-hold	Navigator-gated	Single-shot
1 (n = 71)	2.9 (2.8–3.1)	2.9 (2.6–3.0)	2.7 (2.4–2.9)***,†
2 (n = 73)	2.9 (2.8–3.1)	2.8 (2.6–3.0)**	2.8 (2.6–2.9)***
3 (n = 40)	2.5 (2.2–2.8)	2.8 (2.6–3.0)**	2.7 (2.5–2.9)*
4 (n = 15)	2.4 (2.3–2.7)	2.7 (2.3–3.0)**	2.8 (2.5–2.8)*
1 and 2 (n = 144)	2.9 (2.8–3.1)	2.8 (2.6–3.0)**	2.8 (2.5–2.9)***,†
3 and 4 (n = 55)	2.5 (2.3–2.8)	2.8 (2.6–3.0)***	2.7 (2.5–2.9)**
Overall (n = 199)	2.9 (2.5–3.0)	2.8(2.6–3.0)	2.8 (2.5–2.9)**,††

Image quality is graded on a 5-point scale (4, optimal; 0, not assessable). The image quality scores are presented as median (interquartile range) in each patient group (1, steady plateau; 2, initial drift followed by plateau phase; 3, continuous drift; 4, irregular and unsteady).
$^{***}P<0.001$, $^{**}P<0.01$ vs. breath-hold.
$^{\dagger\dagger}P<0.01$, $^{\dagger}P<0.05$ vs. navigator-gated.