Feasibility study of end-systolic phase imaging for late gadolinium enhancement cardiovascular magnetic resonance imaging

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Purpose

1. Segmented late gadolinium enhancement cardiovascular magnetic resonance (LGE-CMR) imaging is well established for visualizing lesions in patients with both acute and chronic myocardial infarction (MI) [1-5].

2. High heart rate or irregular heart rhythm can cause image artifacts on segmented LGE-CMR images at mid-diastole (MD) [6, 7]. In computed tomography coronary angiography, the cardiac phase for optimal image quality shifts from MD to end-systole (ES) in patients with high heart rates and in the presence of atrial fibrillation (AFib) [8-12].

3. The aims of this study were to evaluate the image quality and infarct size of segmented LGE-CMR at ES as compared with MD in patients with sinus rhythm (SR), and to compare the image quality of ES images in patients with AFib to that of ES and MD images in SR patients.
Methods and Materials

Study populations

Study patients were those with known or suspected coronary artery disease scheduled to undergo a combination of stress-rest perfusion and LGE imaging, who met our inclusion criteria. Exclusion criteria were composed of contraindications to contrast-enhanced CMR examination and to the infusion of adenosine triphosphate, inability to breath-hold during scanning, and patients with non-ischemic cardiac disorders. SR patients with heart rate of ≤55 beats/min and with frequent premature beats (<5/min) were also excluded because of prolonged breath-hold time and the creation of unstable image quality in the respective conditions. The definition for patients with previous MI was based on the medical history according to the European Society of Cardiology/American College of Cardiology consensus document for the redefinition of MI [13]. Study patients were distributed into four groups based on heart rate and rhythm:

1. SR with low heart rate [group-SRL]: ≤65 beats/min (n = 42)
2. SR with intermediate heart rate [group-SRI]: 66-75 beats/min (n = 32)
3. SR with high heart rate [group-SRH]: ≥76 beats/min (n = 34)
4. AFib [group-AFib] (n = 13)

CMR imaging protocol

The combination of stress-rest perfusion and LGE imaging was performed with a 1.5-T scanner using a total dose of 0.15-mmol/kg gadolinium contrast agent. A segmented inversion-recovery gradient-echo (turboFLASH) sequence was used for LGE image acquisition [5, 6]. We obtained short-axis views every 1 cm covering the whole left ventricle, one two-chamber long-axis view, and one four-chamber long-axis view. The acquisition parameters were TR/TE, 7.1 msec/3.3 msec; flip angle, 25°; matrix, 170×240; GRAPPA factor, 2.0; 25 k-space lines per segment; data acquisition window, 177.5 msec; TI, 270 to 340 msec to null normal myocardium; slice thickness, 8 mm; typical in-plane spatial resolution, 2.0×1.4 mm. Data were collected during every other heartbeat to allow adequate T1 relaxation.

In SR patients, ES-imaging was performed first because the longer inversion time required for imaging later would have precluded ES-imaging. Due to the irregular R-R intervals, choosing the optimal intervals of temporal windows was difficult on the MD-imaging of AFib patients, and the image quality could change with each image acquisition. Moreover, arrhythmia often yields electrocardiographic gating failure and
prolongs breath-hold time. For these reasons, MD-imaging was not performed in AFib patients.

Data acquisition window for MD-imaging was placed just before P wave. For ES-imaging, the center of data acquisition window was placed on end-systolic phase measured on cine imaging. Retrospective ECG-triggering in SR patients and prospective ECG-triggering in AFib patients were employed. When the interval between the triggering R wave and end-systolic phase was shorter than the TI, the data acquisition window was set at the earliest phase as possible.

**Image analysis**

The scans were placed in random order and analyzed by two independent observers who were blinded regarding patients’ clinical data and scan parameters.

Image quality, with note of the sharpness of myocardial border and the presence of blurring from cardiac motion, was graded on a 5-point scale (image quality score: 4, optimal image quality; 3, minor motion artifacts; 2, moderate motion artifacts; 1, severe motion artifacts; 0, not assessable). Most apical two short-axis images were omitted from image quality analysis because it was difficult to determine image quality due to partial-volume averaging. The most apical section was defined as the first image with a visible LV lumen; and the most basal section was defined as the first image with an LV outflow or the LV myocardium extended over at least 50% of the circumference. Acceptable image quality for routine clinical diagnostic purposes was considered as image quality score of #2.

LGE-CMRs in patients with documented MI were scored for the presence, location, and the extent of enhanced myocardium using a 17-segment model [14] and a 5-point scale for each segment (0, no hyperenhancement; 1, 1-25%; 2, 26-50%; 3, 51-75%; 4, 76-100%) [2]. 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; ie, 1 = 13%, 2 = 38%, 3 = 63%, 4 = 88%) and divided by 17 [15]. In case of interobserver disagreement as regards the grading of LGE and image quality score, a consensus interpretation was appended.
Results

Reader agreement

Image quality was evaluated in a total of 1534 images in 121 patients. Immediate agreement between two observers for the grading of image quality score was obtained in 87.0% (1334/1534) of images. The agreement between the observers in image quality score was evaluated as good with # values of 0.72. The difference in infarct size in 36 SR patients with documented MI between the two observers was low with a mean bias of 0.5 %LV (limits of agreement ±2.8 %LV).

Effect of heart rate, heart rhythm, and cardiac phase on image quality

The average intervals from the R wave to the center of data acquisition window are shown in Figure 1 on page 7. For every SR patient, the TIs selected by the scanner operators were longer for MD-imaging. The average TIs were 300 ± 17 ms, 315 ± 16 ms, and 298 ± 13 for SR ES-imaging, SR MD-imaging, and AFib ES-imaging, respectively.

Image quality scores are shown in Figure 2 on page 7. ES-imaging had higher image quality than MD-imaging in group-SRH; whereas MD-imaging had higher image quality than ES-imaging in group-SRL and image quality was not significantly different in group-SRI between two imaging (P < 0.05, P = 0.60, P = 0.001, and P = 0.89, in group-SRL, group-SRI, group-SRH, and overall SR patients respectively). Although increased heart rate deteriorated the image quality in MD-imaging, the image quality was not significantly different among groups-SRL, SRI, and SLH in ES-imaging (P < 0.001 in MD-imaging; P = 0.15 in ES-imaging). Meanwhile, image quality of ES-imaging in group-AFib was not significantly different from that in SR patients (P = 0.40 [vs. SR MD-imaging]; P = 0.38 [vs. SR ES-imaging]). Acceptable image quality (image quality score #2) was achieved in 99.6% (721/724) of images in SR MD-imaging, all (724/724) of images in SR ES-imaging, and all (86/86) of images in AFib ES-imaging. Representative images of two patients with AFib are shown in Figure 3 on page 8.

Infarct detection, infarct size, and transmural extent of infarction

Of the 108 SR patients, 36 had documented MI in the medical history. Of the 36 SR patients with known MI, ES-imaging demonstrated LGE in one case in which MD-imaging did not (small left anterior descending artery infarction in Figure 4 on page 9) and neither MD-imaging nor ES-imaging showed LGE in one patient with known non-Q wave MI.
Figure 5 on page 10 displays the comparison of the transmural extent of infarction between MD-imaging and ES-imaging on a regional basis. The concordance was high at 93% (568/612). Figure 6 on page 11 shows the results of Bland-Altman analysis of the difference in infarct size between MD-imaging and ES-imaging. The average difference (bias) was -0.3%LV, and the limits of agreement were ±2.4%LV. There were no systematic differences in infarct size between the two imaging. Representative patient images, demonstrating concordance of hyperenhancement patterns between the two imaging, are shown in Figure 7 on page 12.
<table>
<thead>
<tr>
<th>Group</th>
<th>Mean heart rate (beats/min)</th>
<th>MD-imaging (msec)</th>
<th>ES-imaging (msec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group-SRL (n = 42)</td>
<td>60.8 ± 3.3</td>
<td>734 ± 79</td>
<td>331 ± 25</td>
</tr>
<tr>
<td>Group-SRI (n = 32)</td>
<td>69.8 ± 2.7</td>
<td>656 ± 33</td>
<td>315 ± 20</td>
</tr>
<tr>
<td>Group-SRH (n = 34)</td>
<td>82.7 ± 5.0</td>
<td>544 ± 59</td>
<td>308 ± 19</td>
</tr>
<tr>
<td>Overall SR (n = 108)</td>
<td>70.3 ± 9.9</td>
<td>651 ± 101</td>
<td>319 ± 24</td>
</tr>
<tr>
<td>Group-AFib (n = 13)</td>
<td>74.2 ± 9.9</td>
<td>-†</td>
<td>308 ± 20</td>
</tr>
</tbody>
</table>

†MD-imaging was not performed in group-AFib.

**Fig. 0:** Average intervals from the R wave to the center of data acquisition window.

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<table>
<thead>
<tr>
<th></th>
<th>MD-imaging</th>
<th>ES-imaging</th>
<th>P value</th>
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<tr>
<td>Group-SRL (n = 42)</td>
<td>3.06 ± 0.34</td>
<td>2.95 ± 0.38</td>
<td>&lt;0.05</td>
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<tr>
<td>Group-SRI (n = 32)</td>
<td>2.97 ± 0.35</td>
<td>2.94 ± 0.29</td>
<td>NS</td>
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<tr>
<td>Group-SRH (n = 34)</td>
<td>2.65 ± 0.35</td>
<td>2.81 ± 0.33</td>
<td>0.001</td>
</tr>
<tr>
<td>Overall SR (n = 108)</td>
<td>2.90 ± 0.39</td>
<td>2.90 ± 0.34</td>
<td>NS</td>
</tr>
<tr>
<td>Group-AFib (n = 13)</td>
<td>-†</td>
<td>2.84 ± 0.29</td>
<td>NS*</td>
</tr>
</tbody>
</table>

Image quality score: 4, optimal image quality; 0, not assessable
* vs. overall SR MD-imaging and SR ES-imaging
† MD-imaging was not performed in group-AFib.

**Fig. 0:** Image quality on late gadolinium enhancement cardiovascular magnetic resonance imaging.

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**Fig. 0**: Late gadolinium enhancement images of patients with atrial fibrillation. (Left) Images were obtained at end-systole (center of the data acquisition window, 300 msec). Images showed no hyperenhancement. (Right) Images were obtained at end-systole (center of the data acquisition window, 290 msec). Images showed hyperenhancement in the inferior region (arrow).

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**Fig. 0:** Late gadolinium enhancement images of a patient with known anterior myocardial infarction at heart rate of 72 beats/min. (Left) Both observers missed the hyperenhanced region at the mid-diastolic phase images (center of the data acquisition window, 636 msec). (Right) End-systolic phase images (center of the data acquisition window, 320 msec) showed small hyperenhancement in apical anterior region (arrow) at two-chamber long axis view. However, both images showed no apparent hyperenhancement at short axis views.

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<th>3</th>
<th>4</th>
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<td>1</td>
<td>3</td>
<td>1</td>
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<tr>
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<td>4</td>
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<td>0</td>
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<td>3</td>
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<td>1</td>
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<td>46</td>
<td>1</td>
<td>61</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>446</td>
<td>19</td>
<td>84</td>
<td>56</td>
<td>7</td>
<td>612</td>
</tr>
</tbody>
</table>

0, no hyperenhancement; 1, 1–25%; 2, 26–50%; 3, 51–75%; 4, 76–100%

**Fig. 0:** Comparison of the transmural extent of infarction between MD-imaging and ES-imaging on a regional basis.

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**Fig. 0:** Bland-Altman reproducibility analysis comparing infarct size of left ventricular mass (%LV) between MD-imaging and ES-imaging.

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Fig. 0: Late gadolinium enhancement images of a patient with known anterolateral myocardial infarction at heart rate of 63 beats/min showing concordant hyperenhancement patterns between mid-diastolic phase (center of the data acquisition window, 716 msec) (left) and end-systolic phase imaging (center of the data acquisition window, 306 msec) (right). The presence, location, and transmural extent of the hyperenhanced region were similar in both imaging.

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Conclusion

1. The image quality of ES-imaging is more independent of heart rate compared with MD-imaging. ES-imaging allows employment of segmented method with high spatial resolution and diagnosable image quality for LGE-CMR even in patients with AFib, as well.

2. MI can be accurately detected with the use of ES LGE-CMR imaging as well as MD LGE-CMR imaging in patients with SR.

3. Our results suggest that ES-imaging can be substituted for standard MD-imaging in patients with high heart rates or irregular heart rhythm.
References


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