Effect of temporal resolution on the estimation of left ventricular function by cardiac MR imaging

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Abstract

The aim of this study was to investigate the effect of temporal resolution on the estimation of left ventricular (LV) function by cardiac magnetic resonance (MR) imaging using a steady-state free precession (SSFP) sequence. Left ventricular function was assessed by cine MR imaging using a segmented SSFP sequence in 10 healthy volunteers. Views per segment (VPS) were set at 8 and 20, resulting in high and low true temporal resolution, respectively. Irrespective of VPS, images were reconstructed at 40 cardiac phases, providing high apparent temporal resolution. Data were analyzed using 40, 20 and 10 phases to simulate different apparent temporal resolutions. Increasing the cardiac phases used for analysis slightly decreased mean end-systolic volume (ESV) and slightly increased mean ejection fraction (EF). No substantial difference in estimates of end-diastolic volume (EDV) was found between VPSs of 8 and 20. Imaging with a VPS of 20 yielded a larger ESV and smaller EF than imaging with a VPS of 8 when 40 phases were used. In conclusion, low true temporal resolution causes overestimation of ESV and underestimation of EF. Improvement of apparent temporal resolution mildly reduces but does not eliminate the errors caused by low true temporal resolution.

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1. Introduction

Cardiac magnetic resonance (MR) imaging has become accepted as a reliable method for the noninvasive assessment of left ventricular (LV) function \cite{1,2}. Recently, steady-state free precession (SSFP) sequences, including balanced fast field echo (balanced FFE), true fast imaging with steady-state precession (TrueFISP) and fast imaging employing steady-state acquisition (FIESTA), are being increasingly used for the evaluation of LV volume because they provide high-quality images with excellent blood-myocardial contrast in a short acquisition time \cite{3–10}. k-Space segmentation is usually applied to the MR assessment of LV function. Some of the k-space lines or views for imaging at a given phase of a cardiac cycle are acquired during an RR interval and constitute a data segment \cite{11}. The number of k-space lines included in the segment is called views per segment (VPS). Acquisition is repeated during a single breath hold to obtain all k-space lines. Increasing VPS diminishes the number of cardiac cycles needed to acquire the necessary data and results in a shorter acquisition time, reducing the burden of breath holding. On the other hand, increases in VPS impair temporal resolution. An image at a given cardiac phase is influenced by LV motion during the period of the data segment. Temporal resolution, termed true temporal resolution here, is defined as the length of the data segment, called the acquisition window, and is determined by repetition time (TR) multiplied by VPS. Increases in VPS enhance blurring resulting from LV motion, and image degradation caused by increasing VPS has been described in cardiac MR imaging with an SSFP sequence \cite{12}.
Miller et al. [13] studied the influence of temporal resolution on the MR estimation of LV function with an SSFP sequence and demonstrated that increase in VPS causes underestimation of ejection fraction (EF) despite consistency in estimating end-diastolic volume (EDV). It is supposed that images representing maximal contraction are liable to be missed in low temporal resolution imaging, resulting in overestimation of end-systolic volume (ESV). In their study, a view-sharing technique was not employed. A view-sharing technique makes it possible to use a given k-space line for reconstruction at two or more cardiac phases [14,15]. Without a view-sharing technique, the data segments cannot overlap, and the number of cardiac phases that can be assessed is not more than an RR interval divided by true temporal resolution. When a view-sharing technique is used, the number of reconstructed cardiac phases can be increased, and the interval of adjacent phases, termed apparent temporal resolution here, is shortened. It may be possible that the high apparent temporal resolution attained by a view-sharing technique enables to detect end systole more accurately and eliminates underestimation of EF by low true temporal resolution imaging. The aim of the present study was to investigate whether improvement of apparent temporal resolution compensates for low true temporal resolution in evaluating LV function by MR imaging using an SSFP sequence with k-space segmentation.

2. Methods

2.1. Subjects

Ten healthy male volunteers (age range, 23–48 years; mean age, 34.6±7.8 years) without a history of heart disease or chronic disease were examined in this study. The study protocol was approved by the institutional review board, and all subjects gave written informed consent prior to participating in the study.

2.2. Imaging procedures

Cine MR imaging with electrocardiographic gating was performed on a 1.5-T scanner (Signa CV/i, GE Medical Systems, Milwaukee, WI, USA) with gradient system performance of a maximum amplitude of 40 mT/m and slew rate of 150 T/(m s). A cardiac phased-array coil was used. Images were obtained during breath holds at end-expiratory positions. Contiguous short-axis images covering the entire left ventricle were acquired using a segmented FIESTA sequence. Two sets of images were obtained using VPSs of 8 and 20, resulting in high and low true temporal resolution, respectively. The slice positions for the two imaging sessions were identical. Data were acquired continuously throughout the entire cardiac cycle, and images were generated using retrospective reconstruction [15]. A view-sharing technique is incorporated in the retrospective reconstruction, and the number of reconstructed cardiac phases can be increased in an arbitrary manner. In this study, images at 40 cardiac phases were generated for both sets. Other imaging parameters were as follows: slice thickness of 8 mm, gap of 0 mm, TR of 4.9–6.1 ms, TE of 2.1–2.5 ms, flip angle of 55°, field of view of 24×32 cm and matrix of 96×256. Because TR and TE are related to the orientation of the scanning plane, they varied among subjects.

2.3. Data analysis

The short-axis images obtained were transferred to a workstation (Advantage Windows 4.0, GE Medical Systems), and LV volumes were calculated using dedicated software (Mass Analysis Plus, Medis, Leiden, The Netherlands). Endocardial contours were manually drawn on end-diastolic and end-systolic images, and EDV, ESV and EF were estimated. Papillary muscles were assigned to the LV cavity. The first phase, immediately after the R wave, was defined as end diastole. The end systolic phase was visually determined as the one with the smallest LV cavity, and the same phase was used for all slices. The cardiac phase when the LV cavity seemed the smallest among the total 40 phases was defined, and ESV using 40 cardiac phases was obtained as the LV volume at this phase. In addition, to simulate reconstruction of images at 20 cardiac phases, data analysis was performed using 20 phases with odd numbers. The phase when the LV cavity was the smallest among the 20 phases was determined, and the LV volume at this phase was estimated as ESV using 20 phases. To simulate reconstruction of images at 10 cardiac phases, 10 phases, numbered 4n+1 (n = integer), were used for analysis. End-systolic volume using 10 phases was defined as the LV volume at the phase when the LV cavity was the smallest among the 10 phases. Ejection fractions using 40, 20 and 10 phases were calculated from EDV combined with ESV using

\[ y = 1.037x - 5.8 \]

\[ r = 0.990 \]

Fig. 1. End-diastolic volumes obtained using VPSs of 8 and 20. Solid and broken lines represent the regression line and line of identity, respectively.
40, 20 and 10 phases, respectively. Analyses using 40, 20 and 10 phases represent those based on high-, intermediate- and low apparent temporal resolution imaging, respectively. The VPS-dependent difference was calculated from the results obtained using all 40 phases as an estimate using a VPS of 20 minus that using a VPS of 8.

2.4. Statistical analysis

Data are expressed as means±S.D. Linear regression analysis was performed by the least-square method. Values obtained by different methods were compared by paired t test. A P value of less than .05 was considered statistically significant.

3. Results

Complete sets of short-axis images were acquired in all 10 subjects. Heart rate was 65.6±16.5 and 64.3±16.1 bpm for imaging using VPSs of 8 and 20, respectively. Although both imaging procedures provided image quality sufficient for contour detection and evaluation of LV function, the images obtained using a VPS of 8 tended to be of higher quality with less blurring than those obtained using a VPS of 20.

End-diastolic volume was estimated at 159.9±19.4 ml using a VPS of 8 and at 160.1±20.3 ml using a VPS of 20, with no statistically significant difference found between them. There was a close correlation between EDVs using VPSs of 8 and 20 (r=.990; Fig. 1). The VPS-dependent difference in EDV was 0.2±2.9 ml.

The end-systolic phase determined using 20 cardiac phases was different from that determined using all 40 phases in five subjects for VPSs of both 8 and 20. The end-systolic phase determined using 10 phases was different from that determined using 20 phases in two subjects for VPSs of both 8 and 20. Mean ESV tended to decrease slightly as the number of cardiac phases used for analysis increased (Table 1). For a VPS of 8, statistically significant difference was found between ESVs determined using 40 and 10 phases (P<.05). For a VPS of 20, ESVs determined using 10 phases were significantly larger than those determined using 20 and 40 phases (P<.05 for both). Using all 40 phases, ESV for a VPS of 20 (62.5±10.7 ml) was closely correlated with (r=.961; Fig. 2), but significantly larger than, that for a VPS of 8 (57.5±10.6 ml; P<.001). The VPS-dependent difference in ESV was 5.0±3.0 ml.

### Table 1

<table>
<thead>
<tr>
<th>VPS</th>
<th>ESV (ml)</th>
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<tr>
<td></td>
<td>40 Phases</td>
</tr>
<tr>
<td>8</td>
<td>57.5±10.6</td>
</tr>
<tr>
<td>20</td>
<td>62.5±10.7</td>
</tr>
</tbody>
</table>

Data are presented as means±S.D. Numbers of phases indicate numbers of cardiac phases used for analysis.

### Table 2

<table>
<thead>
<tr>
<th>VPS</th>
<th>EF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40 Phases</td>
</tr>
<tr>
<td>8</td>
<td>64.0±4.4</td>
</tr>
<tr>
<td>20</td>
<td>61.0±4.1</td>
</tr>
</tbody>
</table>

Data are presented as means±S.D. Numbers of phases indicate numbers of cardiac phases used for analysis.

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**Fig. 2.** End-systolic volumes obtained using VPSs of 8 and 20. Forty cardiac phases were used for analysis. Solid and broken lines represent the regression line and line of identity, respectively.

**Fig. 3.** Ejection fractions obtained using VPSs of 8 and 20. Forty cardiac phases were used for analysis. Solid and broken lines represent the regression line and line of identity, respectively.
Mean EF tended to increase as the number of cardiac phases used for analysis increased (Table 2). The difference between EFs determined using 40 and 10 phases reached statistical significance for a VPS of 8 ($P<.01$). For a VPS of 20, EFs determined using 10 phases were significantly smaller than those determined using 20 and 40 phases ($P<.05$ for both). Using all 40 phases, EF for a VPS of 20 (61.0±4.1%) was correlated with ($r=884$; Fig. 3), but significantly smaller than, that for a VPS of 8 (64.0±4.4%; $P<.01$). The VPS-dependent difference in EF was $-31±2.1\%$.

4. Discussion

A view-sharing technique makes it possible to increase cardiac phases assessed by cine MR imaging and to improve apparent temporal resolution [14]. In the present study, images at 40 phases were generated for VPSs of both 8 and 20 using retrospective reconstruction combined with a view-sharing technique. We regarded LV functional parameters obtained with a VPS of 8 and all 40 phases as standards and assessed the influence of reduction in apparent and true temporal resolution. Repetition time ranged from 4.9 to 6.1 ms, and true temporal resolution ranged from 39 to 49 ms and from 98 to 122 ms for imaging using VPSs of 8 and 20, respectively. When true temporal resolution is 100 ms and heart rate is 60 bpm, the number of available cardiac phases is no more than 10 without a view-sharing technique. When 40 phases are assessed using a view-sharing technique and heart rate is 60 bpm, apparent temporal resolution is 25 ms, definitely better than true temporal resolution, especially for a VPS of 20. We used every other phase or every four phases to simulate image reconstructions at 20 and 10 phases, respectively, and investigated the effect of the number of cardiac phases on estimates of LV function. The use of 20 and 10 phases corresponds to apparent temporal resolutions of 50 and 100 ms, respectively, when heart rate is 60 bpm. Irrespective of VPS, increasing the phases used for analysis decreased mean ESV and increased mean EF. Increasing reconstructed phases aids in obtaining images that more accurately represent end systole, which is responsible for the changes in estimated parameters of LV function. However, the changes in mean ESV and mean EF were small.

Increasing VPS shortens acquisition time and, consequently, the burden of breath holding at the expense of true temporal resolution. Low true temporal resolution has been shown to cause underestimation of EF without a view-sharing technique [13]. Without a view-sharing technique, the maximal number of available cardiac phases depends on true temporal resolution, and increases in VPS lead to reduction in cardiac phases. The reduction in phases, in addition to the influence of LV motion during a long acquisition window, may contribute to the underestimation of EF by low true temporal resolution imaging. In the present study, the increase in VPS had no substantial effect on EDV, increased ESV and, consequently, decreased EF even when the same number of phases was used for analysis. Increasing available phases makes it possible to select a phase whose acquisition period corresponds to end systole more accurately. However, the averaging effect of LV motion during a long acquisition window remains for images at each phase. Increasing VPS results in increased blurring from cardiac motion and appears to disturb the collection of accurate end-systolic images. The results of this study suggest that the application of a view-sharing technique to cine cardiac MR imaging with a large VPS mildly reduces but does not eliminate the overestimation of ESV and underestimation of EF caused by low true temporal resolution. In the commercial software used for the estimation of LV volumes in this study, the apparent temporal resolution is presented as a sole marker of temporal resolution. Our results emphasize the importance of the true temporal resolution.

Large VPS shortens the breath-holding time required to obtain cardiac MR images. A long breath hold is a substantial burden especially in patients with LV hypofunction, and reduction in duration should be beneficial. In the present study, an increase in VPS was indicated to cause underestimation of EF even with high apparent temporal resolution. Imaging with a small VPS appears to be preferable when it is applicable to a given clinical situation. The correlation between estimates obtained with VPSs of 8 and 20 was high, despite the systematic differences in the estimates. Measurement of LV function can be performed by cine cardiac MR imaging with a large VPS and is considered justifiable depending on the clinical situation. When a large VPS is used, systematic overestimation of ESV and underestimation of EF should be kept in mind. Only a small number of healthy male volunteers were examined in this study. The degree of error may vary depending on global LV function and the presence of regional hypokinesis; thus, it remains to be defined for various populations.

In conclusion, increasing VPS, leading to low true temporal resolution, does not substantially change estimates of EDV but causes overestimation of ESV and underestimation of EF. Improvement of apparent temporal resolution using a view-sharing technique does not effectively compensate for low true temporal resolution. True temporal resolution, determined by TR and VPS, is important in evaluating LV function by cine cardiac MR imaging using an SSFP sequence.

References


