Comparison of Signal Peak Detection Algorithms for Self-Gated Cardiac Cine MRI

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Abstract

Self-gating (SG) is a cardiac MRI technique to synchronize data acquisition to the cardiac cycle based upon MR signal triggers as opposed to conventional ECG triggers. Fourteen healthy subjects underwent cardiac MRI scans in four different orientations: two chamber, three chamber, four chamber, and short axis. SG trigger times were computed using two methods, first difference and template matching, and ECG trigger times were also recorded for comparison. The root-mean-square (RMS) error was used to evaluate performance, defined as the variability relative to the mean difference between SG trigger times and ECG trigger times. The mean RMS error was lower for template matching than first difference approach for all scan orientations; the improvement in RMS error was statistically significant for all orientations except short axis. In conclusion, compared to the first difference approach, template matching improved the accuracy of trigger detection for two, three, and four chamber SG cardiac MRI scans.

1. Introduction

Cardiac MRI can be technically challenging because data acquisition must be synchronized with the cardiac cycle to avoid motion artifacts. The spatial frequency domain, commonly referred to as *k*-space, is typically filled over multiple cardiac cycles in order to capture all the data needed to create images at each cardiac phase. Retrospective gating for cardiac cine MRI is accomplished by repeatedly sampling each region of *k*-space for a length of time equal to the maximum expected cardiac cycle length; after the scan these datasets are temporally aligned based upon electrocardiogram (ECG) data sampled during the scan. Alternatively, real-time imaging can be used to fill *k*-space in a single cardiac cycle, but the temporal and spatial resolution of gated, segmented approaches are significantly superior.

Retrospective gating is typically accomplished through use of the ECG. The R-wave is usually used for identification of a trigger time since in the normal ECG it has the highest amplitude peak and sharpest upstroke, which simplifies its detection. However, the ECG is corrupted in the MR environment, due to gradient switching [1,2], radiofrequency interference [3,4], and the magnetohydrodynamic effect [5,6]. These sources of interference can cause false triggering, leading to poor MR image quality, particularly in patients with severe heart disease. Consequently, other techniques for gating have been investigated, including vectorcardiography (VCG) [7,8] and self-gating [9,10].

Self-gating (SG) is a triggering technique in which changes in the raw MR data over time are used to form a signal that may be used for triggering. The signal is formed by sampling the center of *k*-space repeatedly over time. This is accomplished by interleaving the pulses used to acquire the SG signal with the pulses used to acquire imaging data. Changes in the cardiac MR signal over time are primarily related to changes in through-plane blood flow velocity and the amount of blood present in the imaging plane, though other moving structures may also contribute. Due to the nature of the SG signal, it does not suffer from the multiple sources of interference which corrupt the ECG and VCG. SG also has the advantage that no lead system is required, resulting in reduced patient setup time. In addition, in principle, SG has the advantage that triggering is dependent upon the intrinsic motion of the heart rather than the electrical activity.

SG is not currently used in the clinical setting for cardiac MRI. One reason may be the lack of robust post-processing algorithms for derivation of synchronization triggers from SG signals. Initial SG approaches used a simple first difference algorithm to detect signal peaks for retrospective gating [9,10]. The objective of our current study was to test whether a more complex trigger detection technique, such as template matching, may be employed to improve trigger detection accuracy.

2. Methods

The study protocol was approved by our institutional review board, and written informed consent was obtained from each subject. Fourteen healthy subjects underwent cardiac MRI scans at four different orientations using a Siemens Magnetom Sonata 1.5 Tesla whole-body clinical MRI scanner. These scans included two chamber, three chamber, four chamber, and short-axis views. Due to scanner time limitations, three of the subjects did not undergo the three chamber scan. SG signals were recorded during each scan from the same 3-4 surface receiver coils used for reception of MR imaging data. ECG trigger times were also simultaneously recorded for comparison.

MATLAB (The MathWorks, Inc., Natick, MA) code was written to perform the signal processing tasks. The SG signals were low-pass filtered to remove high frequency noise and inverted. With 3-4 channels available for each scan, the optimal channel (minimal noise/baseline drift, highest amplitude) was chosen for analysis.

Trigger times were determined by two different approaches, first difference and template matching. The first difference approach consisted of low-pass filtering the signal, taking the first derivative, and identifying positive-to-negative sign changes of the derivative as trigger times. Template matching consisted of creating a median template, computing the cross-correlation of the median template and original signal, and finding the peaks of the cross-correlation signal.

The trigger times identified from both the first difference approach and the template matching approach were compared relative to ECG trigger times. Sample SG signals from all four channels with the trigger times indicated for both approaches as well as ECG trigger times are shown in Figure 1 for a representative subject for a short axis scan. The performance metric used to make the comparison was the root-mean-square (RMS) error, defined as variability relative to the mean difference between SG trigger times and ECG trigger times. The RMS error was calculated using the following equations, where N is the number of triggers, SG(i) is the i^{th} SG trigger and ECG(i) is the i^{th} ECG trigger:

$$\mu(SG-ECG)=\frac{1}{N}\sum_{i=1}^{N}SG(i)-ECG(i)$$

$$RMS(SG-ECG)=\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(SG(i)-ECG(i)-\mu(SG-ECG))^2}$$

Variability relative to this mean was chosen to account for constant phase differences between the triggering schemes. The number of triggers missed for each scan type for each of the methods was also determined by comparison with the ECG triggers.

The difference in RMS errors between the two methods was analyzed by a paired t-test to determine if the improvement in trigger detection was statistically significant.

3. Results

3.1. Subject population

The subject population consisted of fourteen healthy subjects, twelve males and two females. The age among the subject population ranged from 25 to 53 years (mean ± standard deviation, 37 ± 10 years).

3.2. SG signal characteristics

The SG signal was composed of the sum of the thirty-two points in the center of k-space. The duration of the signals used for analysis ranged from 5.67 to 7.35 seconds (7.04 ± 0.64 seconds). The signal duration varied between the subjects due to the different resting heart rates within the subject population. The first 0.75 seconds of each SG signal was discarded to allow the signal to first reach steady state prior to trigger detection analysis.

3.3. RMS errors

The mean and standard deviation of the RMS errors were computed for the four orientation scans for both trigger detection methods; these data as well as the ranges of the RMS errors are summarized in Table 1. The mean RMS errors for the first difference approach were 24.9 ms, 17.3 ms, 20.6 ms, and 10.6 ms compared to 17.4 ms, 12.8 ms, 14.9 ms, and 9.0 ms for the template matching method for the two chamber, three chamber, four chamber, and short axis scans, respectively. Therefore, the mean RMS error was lower for the template matching approach for all scan types. The standard deviation of the RMS errors for the first difference approach were 11.5 ms, 10.9 ms, 7.8 ms, and 4.8 ms compared to 5.7 ms, 7.5 ms, 5.0 ms, and 3.4 ms for the template matching method for the two chamber, three chamber, four chamber, and short axis scans, respectively. Therefore, the standard deviation was also lower for the template matching method for all scan orientations.

No triggers were missed using the first difference method for any scan type. For template matching, no triggers were missed for the four chamber or short axis scans. For the three chamber scan, one trigger was missed for one subject, and for the two chamber scan, one trigger was missed for each of two subjects.

Scan Type	First Difference	Template Matching
Two Chamber	24.9 ± 11.5 ms (7.0 to 42.8 ms)	17.4 ± 5.7 ms (9.1 to 28.8 ms)
Three Chamber	17.3 ± 10.9 ms (8.8 to 47.2 ms)	12.8 ± 7.5 ms (5.9 to 27.1 ms)
Four Chamber	20.6 ± 7.8 ms (7.1 to 34.3 ms)	14.9 ± 5.0 ms (7.5 to 23.2 ms)
Short Axis	10.6 ± 4.8 ms (4.2 to 23.9 ms)	9.0 ± 3.4 ms (3.5 to 13.6 ms)

Table 1: Mean ± standard deviation and range of RMS errors for all four scan types using both first difference and template matching methods for trigger detection.

3.4. Statistical significance

P-values from the paired t-test are shown in Table 2. Using the standard significance level $\alpha = 0.05$, there was a statistically significant improvement for trigger detection for two, three, and four chamber cardiac MRI scans when using the template matching technique compared with the first difference method. There was no statistically significant improvement for the short axis scan.

Scan Type	P-values
Two Chamber	0.006
Three Chamber	0.031
Four Chamber	0.026
Short Axis	0.344

Table 2: P-values for statistical significance between first difference and template matching methods.

4. Discussion and conclusions

Trigger detection for SG was improved by using template matching rather than first difference, specifically for two, three, and four chamber scans. The p-value for the short axis scan indicated that there was no statistically significant improvement when using the template matching approach. Nevertheless, both methods produced results in agreement with anticipated error typically observed in ECG gating due to trigger jitter, which is generally accepted to be approximately 10 to 15 ms [11].

The improvement in trigger detection for two, three, and four chamber cardiac MRI scans when using template matching as opposed to first difference probably arises since SG signals are highly dependent upon in-plane and through-plane blood flow patterns; therefore, two, three, and four chamber orientations may result in more complex signal morphologies. The increased complexity signals present the need for more advanced trigger detection methods, such as template matching, because the first difference approach does not adequately detect triggers within signals acquired at these orientations.

A limitation of this study was that ECG triggering was used as the gold standard, but, as discussed in the *Introduction*, triggering errors can occur due to the multiple sources of interference which corrupt the ECG within the MR environment. However, since in this study only healthy subjects with no known cardiac disease participated, the ECG triggering was most likely accurate since triggering problems are more common with heart disease patients rather than healthy subjects.

In conclusion, though SG is not currently used in clinical practice, improvements in trigger detection may help to take SG one step closer to clinical feasibility.

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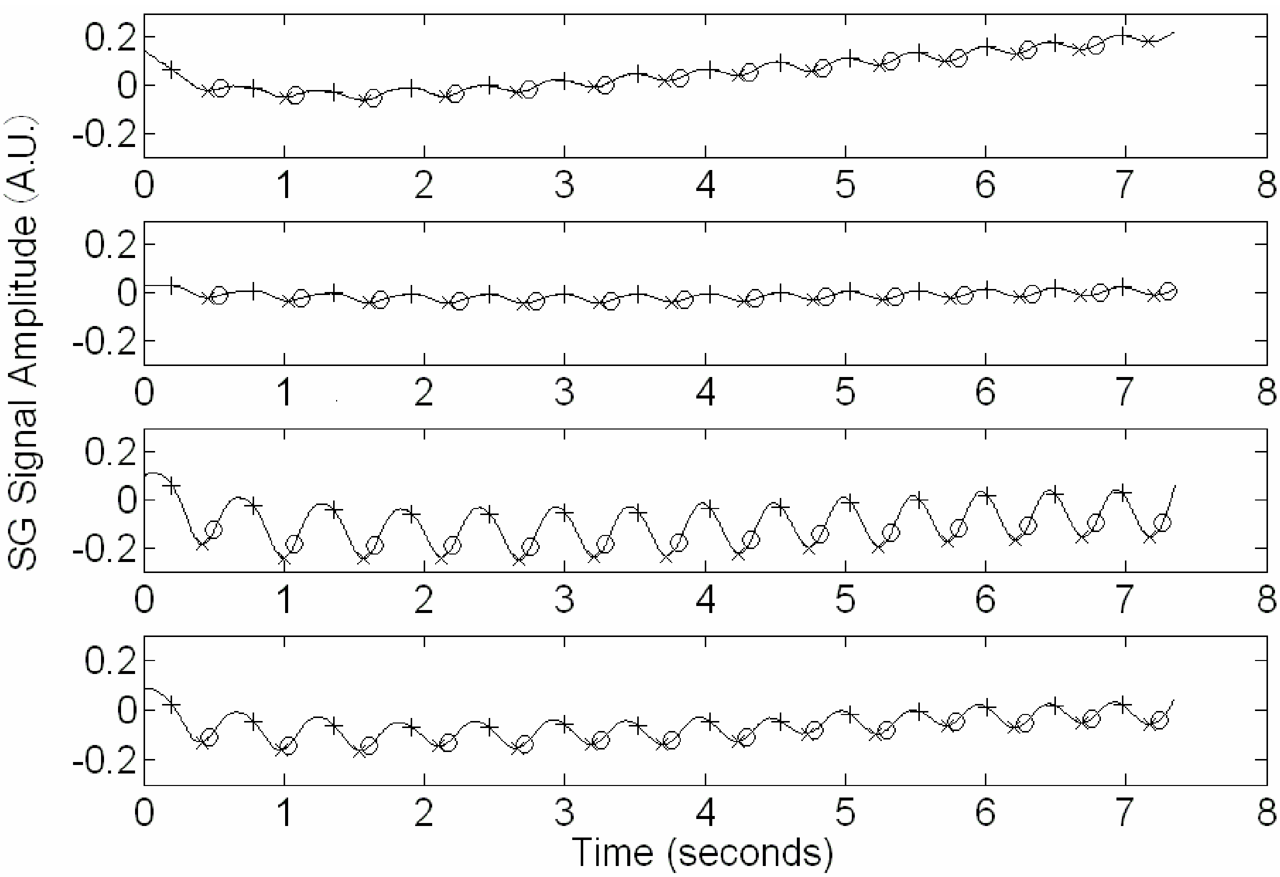

Figure 1: SG signals from all four channels for a short axis scan. On the signals, each "X" indicates a trigger time determined by first difference, "O" indicates a trigger time identified by template matching, and "+" indicates a ECG trigger time.