Accuracy and effectiveness of self-gating signals in free-breathing three-dimensional cardiac cine magnetic resonance imaging*

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Conventional multiple breath-hold two-dimensional (2D) balanced steady-state free precession (SSFP) presents many difficulties in cardiac cine magnetic resonance imaging (MRI). Recently, a self-gated free-breathing three-dimensional (3D) SSFP technique has been proposed as an alternative in many studies. However, the accuracy and effectiveness of self-gating signals have been barely studied before. Since self-gating signals are crucially important in image reconstruction, a systematic study of self-gating signals and comparison with external monitored signals are needed.

Previously developed self-gated free-breathing 3D SSFP techniques are used on twenty-eight healthy volunteers. Both electrocardiographic (ECG) and respiratory bellow signals are also acquired during the scan as external signals. Self-gating signal and external signal are compared by trigger and gating window. Gating window is proposed to evaluate the accuracy and effectiveness of respiratory self-gating signal. Relative deviation of the trigger and root-mean-square-deviation of the cycle duration are calculated. A two-tailed paired t-test is used to identify the difference between self-gating and external signals. A Wilcoxon signed rank test is used to identify the difference between peak and valley self-gating triggers.

The results demonstrate an excellent correlation ($P = 0, R > 0.99$) between self-gating and external triggers. Wilcoxon signed rank test shows that there is no significant difference between peak and valley self-gating triggers for both cardiac ($H = 0, P > 0.10$) and respiratory ($H = 0, P > 0.44$) motions. The difference between self-gating and externally monitored signals is not significant (two-tailed paired-sample t-test: $H = 0, P > 0.90$).

The self-gating signals could demonstrate cardiac and respiratory motion accurately and effectively as ECG and respiratory bellow. The difference between the two methods is not significant and can be explained. Furthermore, few ECG trigger errors appear in some subjects while these errors are not found in self-gating signals.

Keywords: self-gating, free-breathing, cine MRI, effectiveness, accuracy

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1. Introduction

Cardiac cine magnetic resonance imaging (MRI) has been widely used to non-invasively assess cardiac morphology, function and blood flow.[1–3] Conventional cardiac cine MRI is typically based on the segmented data acquired by multiple breath-holds with two-dimensional (2D) or three-dimensional (3D) balanced steady-state free precession (SSFP) pulse sequences.[4–8] In such acquisitions, the breath-hold positions monitored by respiratory bellow (RB) or air bag may be inconsistent, which leads to slice misregistrations or motion artifacts.[9] Furthermore, the RB signal may not accurately reflect respiratory motion if the bellow is not installed at the optimal location. The breath-hold 3D SSFP technique may eliminate slice misregistration limitation and improve the signal-to-noise ratio (SNR).[7,8] However, the long breath-holding time (15 s–20 s) may be difficult for some patients, especially pediatric patients or patients with congestive heart failure.[10] Furthermore, both 2D and 3D SSFP techniques are characterized by limited spatial resolution.[11–13] The conventional 2D breath-hold SSFP technique also requires electrocardiographic (ECG) gating as the external trigger to synchronize cardiac motion.[6–8] However, in some cases, ECG triggers are unreliable because of the influence of the magnetic field of the MRI system or the physiological abnormalities of the patient.[9,14] Inaccurate ECG triggers will compromise the accuracy of *k*-space data of each cardiac phase. Therefore, triggering errors constitutes an additional disadvantage in ECG gated cardiac cine MRI.[9]

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Cardiac and respiratory self-gated free-breathing SSFP has recently been proposed as an alternative to conventional breath-hold SSFP for cardiac cine MRI.[15–18] Free-breathing acquisition enables better spatial resolution. Self-gating signals derived from the *k*-space data can theoretically and technically replace the external gating signals. There are many methods to obtain self-gating signals, such as *k*-space center data points,[9] *k*-space lines across the *k*-space center,[17] or low-resolution images.[19,20] However, the accuracy and effectiveness of self-gating signals have been barely systematically studied.

In this study, external monitored signals are simultaneously acquired by ECG and RB devices during the free-breathing 3D SSFP acquisition. Self-gating signals are derived via repeated acquisition of the *k*-space centers along the *z*-direction.[16] The accuracy and effectiveness of the self-gating signals are evaluated by comparing with external monitored signals.

2. Materials and methods

2.1. Human Scans

A previously described self-gated free-breathing 3D SSFP technique[16] was used. Twenty-eight healthy volunteers (16 males and 12 females), whose ages ranged from 25 to 35 years (median age 30.5 years), were included in this study. The self-gated free-breathing 3D SSFP technique was performed on a 1.5-T GE HDx scanner (maximum gradient amplitude 33 mT/m, slew-rate 120 (mT/m)/s, Excite 14M5 platform; GE Healthcare, Waukesha, WI, USA). The study was approved by the local institutional review board at Weill Cornell Medical College, and written informed consent was obtained from all subjects prior to enrollment. An eight-channel cardiac phased-array coil was used for signal collection. The cine imaging parameters were set as follows: TR/TE = 3.5/1.3 ms, flip angle = 40°, bandwidth = ±125 kHz, slice thickness = 7 mm (no gap), number of slices = 12–14, number of profiles = 5000, and total acquisition time ≈ 5 min.

2.2. Data analysis

The heart/breath rate and the cardiac/respiratory cycle duration were compared between the self-gating and ECG/RB methods. Trigger positions were evaluated by calculating the correlation coefficients and trigger deviation time of the two methods. The triggers of the self-gating signals were determined by the signal peaks and valleys. A Wilcoxon signed rank test with a two-sided alpha of 0.05 was used to identify differences between peak and valley triggers. There were individual differences in the heartbeat and breath patterns among the healthy volunteers; thus, the relative deviation between the self-gating and external triggers was calculated via the following formula:

$$\mathrm{RD} = \frac{\sum_{i=1}^{M} \left| t_{\mathrm{ECG/RB}i} - t_{\mathrm{SG}i} \right| / t_{\mathrm{ECG/RB}i}}{M} \times 100\%, \qquad (1)$$

where $t_{\mathrm{ECG/RB}i}$ and $t_{\mathrm{SG}i}$ represent the i-th cycle duration of the monitored and self-gating signals, respectively (Fig. 1); M denotes the number of cycles. Furthermore, the root-mean-square-deviation (RMSD) between the cardiac/respiratory cycle durations of the two methods were calculated. A two-tailed paired t-test was used to identify the differences, with p-value of less than 0.05 considered statistically significant.

Figure 1 shows the diagram of the signal pre-synchronization. The ECG signal (Fig. 1(a)) was acquired with the temporal resolution of t_{resol}. The i-th ECG trigger is denoted as $n_{\mathrm{ECGtrig}i}$, which represents the data point number of the i-th cardiac cycle. The corresponding profile acquisition diagram is shown in Fig. 1(b), and p_{tirgi} represents the profile number. The CSG signal with a temporal resolution of $n_z \cdot \mathrm{TR}$ is shown in Fig. 1(c). The theoretical basis and trigger selection of two methods are different; thus, there is a trigger deviation time between them (denoted as $t_{\mathrm{trig\ dev}}$ in Fig. 1(c)). The peak is selected as CSG trigger in Fig. 1 only as an example. Note that a positive trigger deviation time indicates that the external trigger occurs prior to the corresponding self-gating trigger, and a negative trigger deviation time expresses the opposite meaning. $t_{\mathrm{ECG}i}$ and $t_{\mathrm{CSG}i}$ represent the i-th cardiac cycle duration in the ECG and CSG signals, respectively.

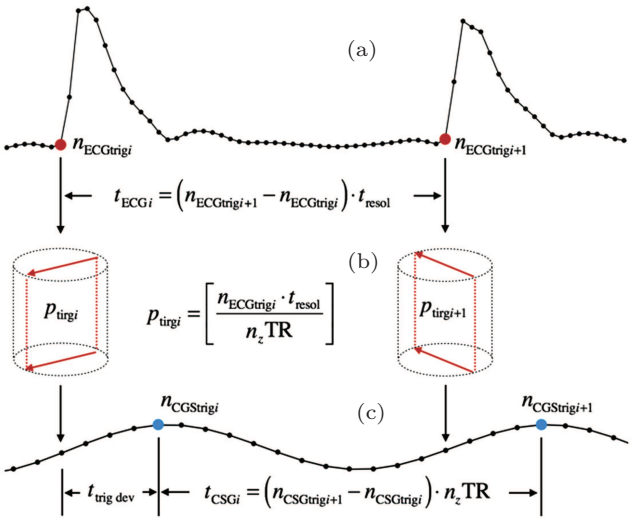


Fig. 1. (color online) Diagram of signal pre-synchronization. ECG signal (a), corresponding *k*-space profile acquisition diagram (b), and CSG signal (c) are presented. The red and blue points represent the ECG and CSG triggers, respectively. Note that the black points of the signal curves represent the monitored ECG signal data (a) and derived CSG signal data (c).

Figure 2 shows the diagram of respiratory motion comparison. The motions from two methods are denoted as blue (RSG) and red (RB) curves. In the self-gated free-breathing imaging technique, a respiratory histogram was calculated from the RSG signal, and the data within the given gating

windows chosen around the histogram peaks were used for image reconstruction.[16,17] Therefore, for evaluating the accuracy and effectiveness of the RSG signals, the percentages of the acquired data within both the RSG and RB gating windows (green upward arrows in Fig. 2) were calculated.

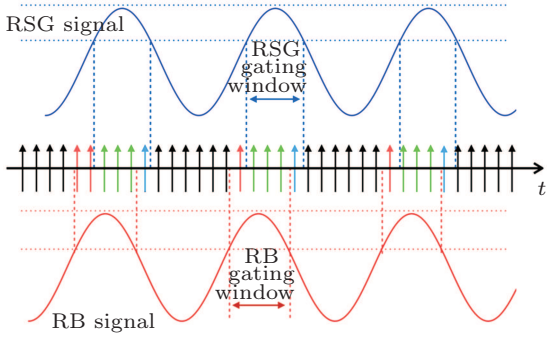


Fig. 2. (color online) Diagram of respiratory motion comparison. The blue and red curves represent the RSG and RB signals, respectively. The upward arrows represent the acquired data. The blue, red, and green upward arrows denote the acquired data within the RSG gating windows only, within the RB gating windows only, and within both the RSG and RB gating windows, respectively.

3. Results

All subjects are successfully acquired with the free-breathing self-gated 3D SSFP sequence. Twenty-five cases are included in the data analysis because three cases failed to provide effective externally monitored signals or triggers for comparison. The cardiac cycle duration (*R*–*R* intervals) and the respiratory cycle duration of 25 subjects are 751.3±93.1 ms (which corresponds to 81.1±10.3 beats per minute) and 3314.7±1072.6 ms (which corresponds to 19.5±4.5 breaths per minute), respectively.

Figure 3 shows the synchronized self-gating and externally monitored signals from one representative subject with a cardiac cycle duration of 911.7 ms and respiratory cycle duration of 2483.1 ms. Figure 4 shows the comparisons of cine images reconstructed via self-gating signals (Fig. 4(a)) and external monitored signals (Fig. 4(b)) from the same subject. Image subtractions between two methods are shown in Fig. 4(c). The difference between two reconstructed cine images is small (0.71%). The gating signals of this subject are also compared. For cardiac motion, the relative deviation is 4.19% for both peak and valley triggers, and the RMSDs are 45.5 ms (peak) and 48.2 ms (valley). For respiratory motion, the relative deviation and RMSD are 7.92% and 335.1 ms (peak) compared with 5.75% and 196.3 ms (valley). The profile data within both RSG and RB gating windows are 94.2%.

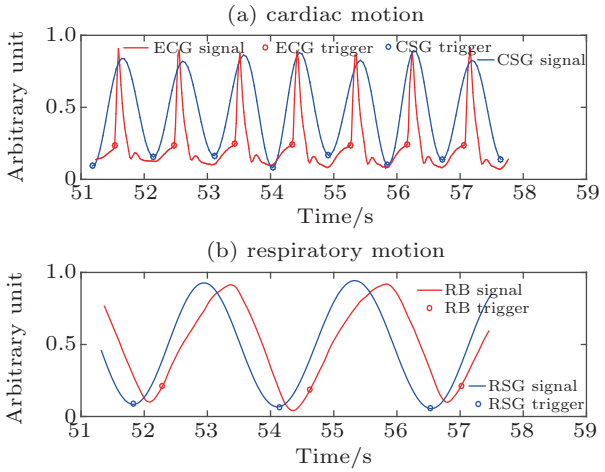


Fig. 3. (color online) Comparisons of synchronized self-gating signals and peripheral monitor signals from a volunteer. ECG (red line) and CSG (blue line) signals are shown in panel (a), and RB (red line) and RSG (blue line) signals are shown in panel (b). Triggers of each method are shown as red and blue points. The amplitudes of all curves are rescaled for comparison only.

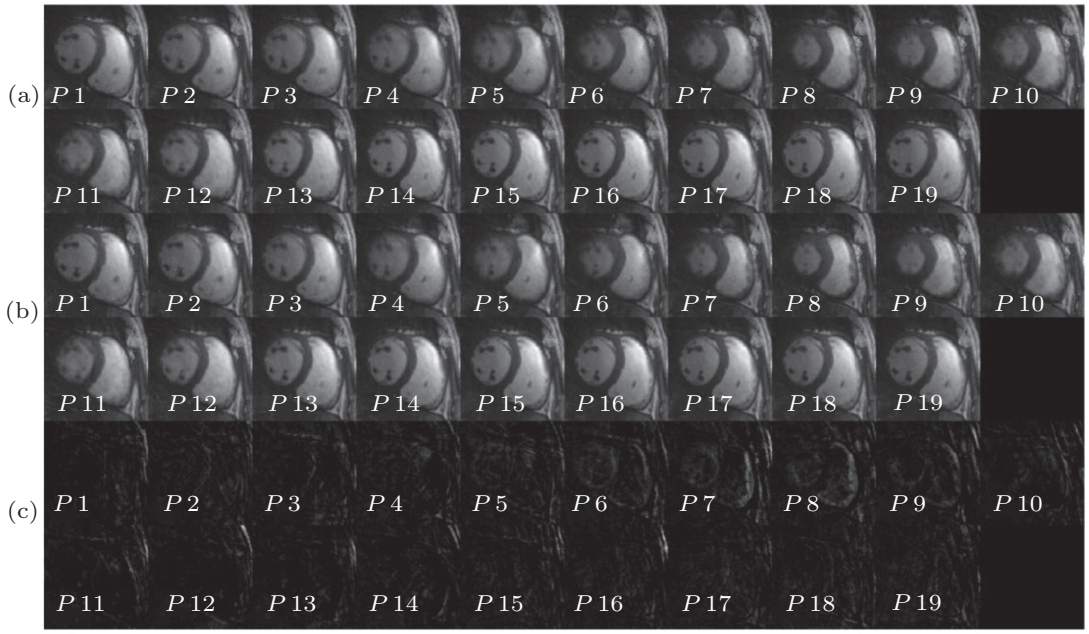


Fig. 4. Comparisons of cardiac cine images reconstructed via self-gating signals (a) and external signals (b), (c) shows the difference between panels (a) and (b). All cardiac phase images of the mid-slice are presented, and *Pm* represents the *m*-th cardiac phase image.

The cardiac and respiratory signal comparisons between the two methods are summarized in Tables 1 and 2. The relative deviation values, the ratios of the RMSD to the mean cycle durations and the trigger deviation times are presented as the mean± SD of the 25 cases. The results of Wilcoxon signed rank test indicate that there is no significant difference between peak and valley triggers for both cardiac ($H = 0$, $P > 0.10$) and respiratory ($H = 0$, $P > 0.44$) signals. However, the relative deviation and RMSD of the peak CSG and valley RSG triggers are smaller, which indicates that the peak CSG triggers and valley RSG triggers enable better synchronization with the corresponding ECG and RB triggers. The correlation coefficients of all cases are greater than 0.99 ($P = 0$) for both cardiac and respiratory triggers, which suggests that there is an excellent correlation between the two methods. The P values of the two-tailed paired-sample t-tests of all cases are greater than 0.95 ($H = 0$) for cardiac motion and greater than 0.90 ($H = 0$) for respiratory motion. This finding indicates that there is no significant difference between the externally monitored and self-gating techniques.

Table 1. Cardiac motion comparison between the self-gating and externally monitored signals.

	Trigger from peak	Trigger from valley
Relative deviation/%	3.81±0.98	4.39±1.39
RMSD/Mean cycle duration/%	5.33±1.84	5.91±1.99
Trigger deviation/ms	115.3±46.8	489.4±70.8
Correlation with ECG ($P = 0$)	> 0.99	> 0.99
t-test P value (H =0)	> 0.95	> 0.95

Table 2. Respiratory motion comparison between the self-gating and externally monitored signals.

	Trigger from peak	Trigger from valley
Relative deviation/%	8.32±2.95	5.15±2.02
RMSD/Mean cycle duration/%	10.99±4.00	6.76±2.97
Trigger deviation/ms	1242.4±649.6	–491.7±310.0
Correlation with RB ($P = 0$)	> 0.99	> 0.99
t-test P value ($H = 0$)	> 0.90	> 0.90

Figure 5 shows the statistical results of the ratios of the RMSD to the cycle duration of all cases. The triggers from the peaks and valleys of the self-gating signals were compared. For cardiac motion, 72% and 96% (peak trigger) of the cases are smaller than 0.06 and 0.08, respectively, compared with 64% and 84% (valley trigger). For respiratory motion, 24% and 80% (peak trigger) of the cases are smaller than 0.08 and 0.12, respectively, compared with 68% and 100% (valley trigger). The results demonstrate that peak CSG triggers and valley RSG triggers enable better synchronization with external triggers.

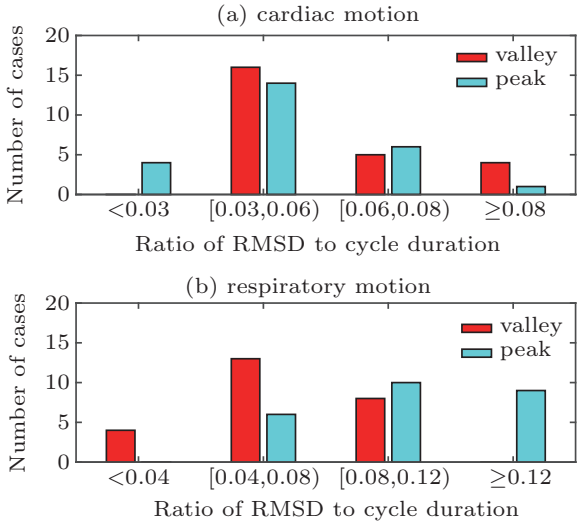


Fig. 5. (color online) Statistical results of the ratios of the RMSD to cycle duration. Triggers from peaks and valleys of the self-gating signals are compared.

Figure 6 shows the percentages of the acquired k-space data within both the RSG and RB gating windows. The same profiles used for reconstruction are 59.1±8.6% with 30% gating windows and 80.5±7.9% with 50% gating windows. High similarity between the RSG and RB signals is identified in 50% reconstruction gating windows.

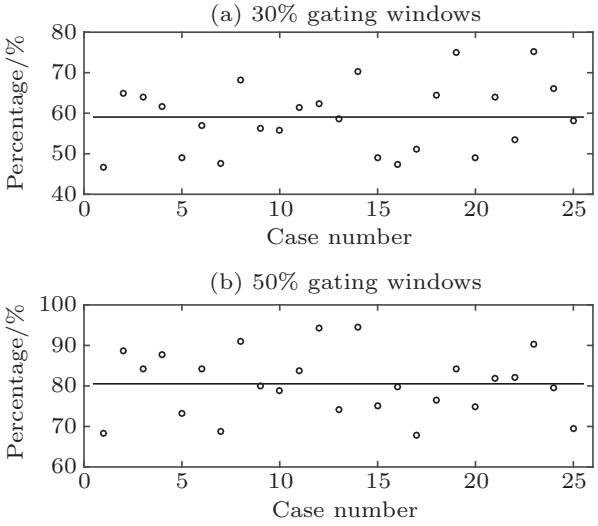


Fig. 6. Percentages of the data within both the RSG and RB gating windows corresponding to 30% (a) and 50% (b) gating windows. Each point represents one case. The black line represents the average level.

Figure 7 shows a representative case where the ECG fails to accurately record the triggers because of magnetohydrodynamic interference. The wrong trigger position will cause the k-space data to be sorted into the incorrect cardiac phases. Figure 8 shows a representative case with a distorted RB signal. As a result of truncation problems, the RB signal may not accurately reflect the respiratory motion, and the accuracy of the RB triggers will also be affected. In this study, there are three cases about these problems, which indicate that the conventional ECG or RB methods may be unreliable in free-breathing MRI.

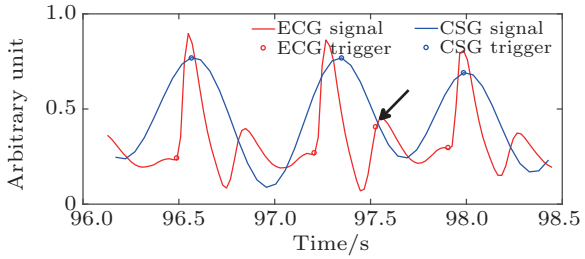


Fig. 7. (color online) An inaccurate ECG trigger (indicated by the black arrow) is recorded in a representative case. The amplitudes of all curves are rescaled for comparison only.

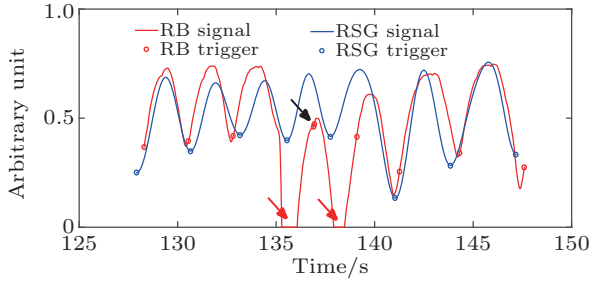


Fig. 8. (color online) A representative case with a distorted RB signal. An inaccurate RB trigger (indicated by the black arrow) is recorded as a result of signal distortion (indicated by the red arrows). The amplitudes of all curves are rescaled for comparison only.

4. Discussion and conclusions

Conventional cardiac cine MRI is typically performed by using multiple breath-hold techniques. The newly proposed self-gated free-breathing 3D SSFP technique enables the completion of the scan with neither peripheral monitors nor breath-holds. In this study, the accuracies and effectiveness of the self-gating signals are systematically investigated by comparing the self-gating signals with the synchronized externally monitored signals.

Self-gating signals directly reflect the cardiac and respiratory motion compared with the externally monitored signals. The two-sided Wilcoxon signed-rank test shows that there is no significant difference between peak and valley triggers at the 5% significance level for self-gating signals. However, the relative deviation and statistical analysis of RMSD show that the peak CSG and valley RSG triggers enable better synchronization with the corresponding external triggers. For cardiac motion, an ECG signal reflects the cardiac electric activity,[21,22] and ECG triggers are recorded in atrial systoles. The CSG signal reflects the change in heart blood volume.[17] Thus, the MR signal intensity increases during diastole. The peaks of self-gating signals correspond to end-diastoles. Therefore, the differences between peak triggers and ECG triggers are smaller, and the trigger deviation time of peak triggers is shorter. For respiratory motion, RB triggers are recorded in the early phase of expiration. Valleys of the RSG signal correspond to end-inspiration. Furthermore, as a result of the respiratory signal fluctuation at the end of expiration for some volunteers, an accurate detection of peak is difficult. Therefore, the difference between the valley trigger and RB trigger is smaller, and the absolute trigger deviation time of the valley trigger is shorter. Note that a negative deviation time denotes the external trigger occurs prior to its corresponding self-gating trigger. Furthermore, the temporal resolutions of the self-gating signal and monitored signal are different.

Conventional cardiac cine MRI typically requires ECG triggers to synchronize the *k*-space data acquisition with cardiac motion. However, rapid switching of the magnetic field gradients will compromise the accuracy of ECG trigger because of the magnetohydrodynamic effect. Patients with abnormalities in cardiovascular structures or chest geometry may exhibit low-amplitude ECG signals that make it difficult to implement the trigger selection.[9] The inaccurately recorded ECG triggers (shown in Fig. 7) would subsequently lead to inappropriately triggering for data acquisition. However, the CSG signal is based on the intrinsic cardiac motion, and CSG triggers are selected as the peaks or valleys of the CSG signal. Thus, the self-gated imaging technique will not suffer this problem.

In this study, a novel method is introduced to evaluate the RSG signals. In the free-breathing acquisition, the acquired *k*-space data within the given gating windows are used for image reconstruction.[16] The gating windows need to balance the undersampling artifacts (narrower gating windows) and motion blurring (larger gating windows).[16,17] Therefore, the similarity between the RSG and RB signals compared by the locations of these gating windows is proposed to compare the respiratory signals. The percentages of data located in both the RSG and RB gating windows are calculated. Figure 6 indicates that there are 59.1±8.6% (more than 46.7% for all cases) and 80.5±7.9% (more than 67.8% for all cases) of the profiles located in both of the gating windows when the gating windows are set to be 30% and 50%, respectively. These findings indicate that the RSG signal highly synchronizes with the RB. The acquired data within 50% RSG gating windows are sufficiently effective in reconstructing the free-breathing images as shown in Fig. 4. However, the difference between RSG and RB signals in Fig. 6 may be caused by different respiratory motion directions detected. The RB signal directly reflects the respiratory motion in the post-anterior direction, whereas the derived RSG signal reflects the respiratory motion that affects the heartbeat (approximately in the long-axis direction). Furthermore, the RB signal may not accurately reflect the respiratory motion because of the signal distortion(shown in Fig. 8).

In this study, all subjects are healthy volunteers who are assumed to have a regular heartbeat and respiration. However, some patients, especially patients who suffer from cardiac arrhythmias, have irregular heartbeats.[23–27] Therefore, the accuracy and effectiveness of self-gating signals in these subjects requires further investigation. In addition, the *k*-space sampling scheme of data acquisition adopted in this study is mod-

ified from a 3D golden-ratio based radial sampling scheme. However, there are many other methods used to obtain self-gating signals, such as the respiratory self-gated multiple-gradient recalled echo sequence[28,29] and manifold learning-based 2D golden-ratio based radial SSFP technique.[30] Therefore, the accuracy and effectiveness of self-gating signals obtained with other sampling schemes and comparisons between them also require further investigation.

In conclusion, there is no statistically significant difference between self-gated free-breathing SSFP and conventional ECG/RB techniques. Self-gating signals synchronize well with externally monitored signals and provide approximately the same cardiac cycle duration and respiratory cycle duration compared with the monitored signals. There is no significant difference between peak and valley triggers for both cardiac and respiratory motions. However, peak CSG triggers and valley RSG triggers enable better synchronization with the corresponding external triggers and are more effective. Furthermore, self-gating triggers are more reliable than external triggers in free-breathing imaging.

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