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# Free-Breathing Self-Navigated Isotropic 3-D CINE Imaging of the Whole Heart using Adaptive Triggering and Retrospective Gating

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## Synopsis

We present a method for free-breathing whole-heart 3-D CINE imaging based on adaptive triggering and retrospective gating and compare it to a previously published method using prospective triggering. We show that our method is simultaneously robust to heart-rate variability during the scan and able to cover the entire cardiac cycle, which is not the case for prospective triggering. A validation in 6 volunteers shows reduced end-diastolic volume bias compared to a gold-standard 2-D reference for our method. Image reconstruction is integrated into the scanner system and takes less than 3 minutes.

## Purpose

In clinical practice, cardiac function parameter estimation is based on multi-breath-hold 2-D CINE imaging, featuring high in-plane resolution, but thick slices. 3-D CINE acquisitions with isotropic resolution have been proposed,<sup>1-3</sup> but require long reconstruction times,<sup>1</sup> long breath-holds<sup>2</sup> or prospective triggering (PT) to synchronize the acquisition to the heartbeat.<sup>2,3</sup> However, PT may not be able to acquire the entire cardiac cycle and can cause image artifacts in the presence of heart-rate variability. In this work, we extend a recent method<sup>3</sup> to use adaptive triggering and retrospective gating (ATRG), which may solve these issues.

## Methods

In PT acquisitions, a fixed acquisition window for each heartbeat is defined before the scan is started. While PT with a short acquisition window is commonly used in case of cardiac arrhythmia, the late diastolic phase of the cardiac cycle might be missed and PT provides no guarantee that actual cardiac state and assigned phase for reconstruction correspond (see Figure 1, top). ATRG allows for a continuous acquisition in the presence of heart-rate variability, where the acquisition window for each heartbeat matches its length, but leads to a varying number of cardiac phases for each heartbeat (see Figure 1, bottom). Retrospective gating of this data to a reference heartbeat is commonly done by linear interpolation, which can cause artifacts in the presence of arrhythmia. To prevent artifacts due to arrhythmia and ensure correlation between actual cardiac state and assigned phase, we selected a model where the first 300 ms correspond to a fixed-length systole and the remaining time is a variable-length diastole which is linearly stretched to the reference heartbeat (see Figure 2).

The previously proposed sampling pattern<sup>3</sup> is well suited for ATRG because of the golden-angle increment of the spiral arms, allowing retrospective rebinning while ensuring sufficient k-space coverage.

Whole-heart, free-breathing 3-D CINE imaging with PT and ATRG in short-axis (SA) orientation was performed in 6 healthy volunteers (2 female, age  $27 \pm 4$ ) on a 1.5 T clinical MR scanner (MAGNETOM Aera, Siemens Healthcare, Erlangen, Germany). A 3-D volume-selective bSSFP prototype imaging sequence with the following parameters was used: TR 2.6 ms, TE 1.3 ms,  $\alpha = 39^\circ$ , FOV  $365 \times (320 \pm 28) \times 152 \text{ mm}^3$ , acquired voxel size  $(1.9 \text{ mm})^3$ , measured temporal resolution 42 ms, 20 computed phases, fixed acceleration factor of 3.1 compared to the fully-sampled matrix and a receiver bandwidth of 1000 Hz/px. For signal reception, 18 + 12 elements of an anterior + posterior local coil matrix were used. For reference, a 12-slice SA 2-D bSSFP acquisition with  $\alpha = 54^\circ$  and retrospective ECG gating in multiple breath-holds was performed to cover the LV with similar temporal resolution, identical in-plane resolution and a slice thickness of 8 mm.

Compressed sensing reconstruction was performed as previously presented,<sup>3,4</sup> with one modification in the regularization term. While redundant wavelets were used previously, orthogonal wavelets and cycle spinning were employed in our method to retain translation invariance while reducing the memory footprint and required computation time. The image reconstruction was fully integrated into the scanner software and multi-GPU accelerated.

For evaluation, we compared the acquisition and reconstruction times, ventricular function (VF) parameters computed manually from the images of the gold standard 2-D CINE and PT and ATRG 3-D CINE in corresponding slices of all data sets as well as the Hausdorff distance<sup>5</sup> of the segmented blood pool in the first and last phases of PT and ATRG acquisitions to measure if the entire cardiac cycle was captured.

## Results and Discussion

Five out of six volunteers showed considerable heart rate variability leading to skipped triggers even for conservatively selected acquisition windows. Acquisition time was  $4 \text{ min } 43 \text{ s} \pm 32 \text{ s}$ , reconstruction time was  $2 \text{ min } 38 \text{ s} \pm 27 \text{ s}$  for ATRG and comparable for PT. For qualitative results, see Figure 3. Bland-Altman plots for VF parameters are shown in Figure 4. The Hausdorff distance between first and last phase was  $5.5 \pm 1.1 \text{ mm}$  for PT and  $3.4 \pm 0.9 \text{ mm}$  for ATRG.

ATRG acquisitions show less EDV bias because the entire diastole is acquired, also confirmed by the smaller Hausdorff distance. The EDV bias of PT is in line with other published results.<sup>6</sup> With ATRG, it is not necessary to choose an appropriate acquisition window. The use of the orthogonal wavelet transform and cycle spinning leads to a reduction of 57 % in reconstruction time compared to previously published work.<sup>3</sup>

## Conclusion

With ATRG, 3-D CINE imaging can be performed without the need to select an appropriate acquisition window and is robust to heart-rate variation. Coverage of the entire cardiac cycle can be achieved, leading to reduced VF bias. Full scanner integration and reconstruction times of less than 3 min improve the clinical relevance of the presented method.

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References

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Figures



Figure 1: With prospective ECG triggering (top row), acquisition is performed for a fixed amount of time (acquisition window) after each ECG R peak. If an R peak occurs within an active acquisition window (denoted in red), the acquisition continues and the next heartbeat is skipped for acquisition. However, in this case the heart is already contracting again, but the acquired data is assigned to end-diastolic phases. This causes a mismatch between the real cardiac state of the acquired data and the phase to which it is assigned for reconstruction. With adaptive ECG triggering (bottom row), acquisition is performed continuously.

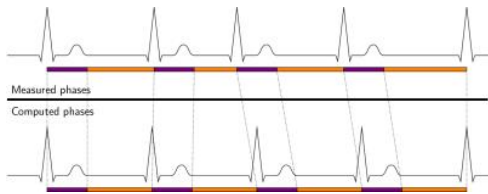


Figure 2: The measured phases are split into systolic (purple) for the first 300 ms after the R peak and diastolic (orange) for the remaining data until the next R peak. Computed phases are then mapped 1-to-1 for systolic data and linearly stretched for diastolic data to a reference cardiac cycle whose length corresponds to the mean acquired RR interval.

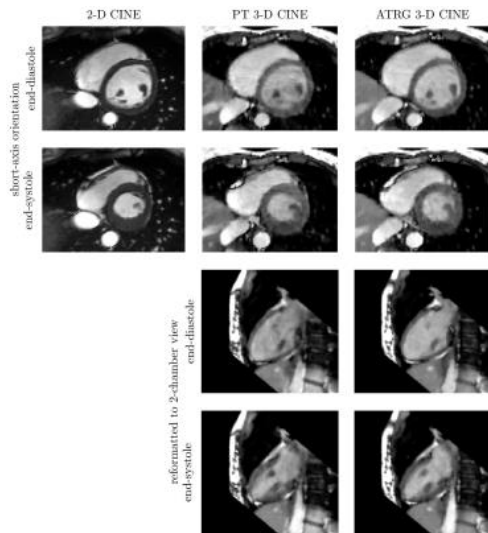


Figure 3: Qualitative results for short-axis 2-D CINE and corresponding short-axis slices of PT and ATRG 3-D CINE, as well as reformatted slices from the isotropic datasets in 2-chamber view. The increased artifact level in PT images may be due to the previously mentioned mismatch between real cardiac state and assigned cardiac phase, as there was considerable heart-rate variation during the acquisition.