Dark rim artifacts from motion in highly accelerated 3D cardiac perfusion imaging

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PURPOSE: First-pass myocardial perfusion imaging is a promising method for characterizing ischemic heart disease. 3D acquisitions are also desirable since they can provide greater coverage of the heart than 2D imaging, with more accurate estimation of the size of ischemia [1]. However, 3D imaging requires a much longer readout than the 2D case, leading to more artifacts than 2D acquisitions even when acceleration schemes are used. Dark rim artifacts are one of the major factors that impede accurate quantification and diagnosis of ischemia even when the image quality is otherwise reasonable [2]. Dark rim artifacts are not yet completely understood even in 2D perfusion imaging, although Gibbs ringing and cardiac motion are thought to be the main contributing factors [2,3,4]. In this work, we demonstrate that motion can explain the dark rim artifacts we observe in a highly-accelerated 3D acquisition scheme for first-pass myocardial perfusion imaging. We also show that dark rim artifacts are sensitive to both k-space trajectory and the timing of motion relative to the readout.

METHODS: We modified a 3D saturation-recovery TurboFLASH pulse sequence to enable arbitrary phase encode (PE) ordering for a highly-accelerated acquisition. We used an acceleration factor R = 11 with a variable density phase encode mask. We implemented both centric and reverse-centric phase encode orderings, and interleaved the two trajectories every other temporal frame as shown in Fig 1. Pairs of adjacent time frames share the same undersampling mask, but one belongs to the reverse centric acquisition and one to the centric acquisition. This allows us to achieve a relatively fair comparison between these two phase encode orderings. The sequence was implemented on a 3T Siemens Verio whole-body scanner (Siemens Medical Systems, Erlangen, Germany). The acquisition matrix was 144 x 108 x 10 (including 25% oversample in slice direction) with 110 temporal frames. With an acceleration factor R = 11, there were 98 phase encodes for one time frame and TR/TE = 2.6/1.1ms. A non-selective saturation recovery pulse with TI = 150ms triggered by the ECG signal was also applied. Readout bandwidth was 1152 Hz/pixel and the flip angle was 12 deg.

Simulations: A numerical simulation was designed to estimate the motion artifacts using a numerical heart phantom that mimics the initial high contrast agent concentration in the left ventricular blood pool. The simulation applied the appropriate signal weightings in k-space based on the saturation recovery sequence. We used the same acquisition mask was as we did in the real scan. In order to simulate the motion, we applied physical shifts to the numerical phantom in the phase encode direction at different times (after 5PEs, 10 PEs, 20 PEs 30PEs, 40PEs, 50PEs, 60PEs, 70PEs, 80PEs and 90PEs). Image reconstruction was performed using a compressed sensing algorithm with total variation (TV) applied as the constraint term in both the temporal and spatial directions for both real and simulated data [5].

In Vivo Experiments: The sequence was tested in vivo on a canine and 3 human subjects with a 32-channel coil. Image reconstruction was performed offline using the TV reconstruction.

RESULTS: We observed severe dark rim artifacts using centric ordering in one of the in vivo datasets, shown in Fig 2. We were able to simulate a similar artifact by shifting the virtual phantom during the early phase encodes, shown in Fig 3. We observed that dark rim artifacts are sensitive not only to motion, but also the time during readout at which the motion occurs. From the simulation, it can be seen that if the motion occurs close to the time when the center of k-space is sampled, the artifacts are more severe. This is seen when the shift happens after the 5th PEs and 10th PEs for a centric phase encode order, and at the 90th PEs for a reverse-centric order. Very little artifact is observed when the shift occurs near the middle phase encodes of the acquisition. For example, motion near the 50th PEs causes very little artifact in both centric and reverse centric scans.

DISCUSSION: These results extend work by others [2,3,4] that showed from GRE scans that motion in 2D acquisitions could in theory produce dark rim artifacts. The relatively long 3D acquisition here is likely more sensitive to motion, and simulations were used to show that simple translations such as from sudden respiratory or cardiac motion can generate dark rim artifacts in undersampled 3D acquisitions. Moreover, the PE ordering plays a role since effects are larger when the center of k-space is sampled during significant cardiac motion. Based on this result, one could devise phase encode ordering schemes to mitigate dark rim artifact. For example, occasionally revisiting the center of k-space might allow for a method to reduce the severity of dark rim artifact caused by motion.

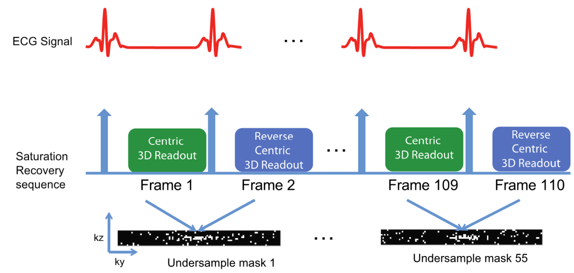

FIG 1: The acquisition scheme for the comparison between centric and reverse-centric trajectories. Two adjacent acquisition frames share the same pseudo-random undersampling mask, but with reversed path.

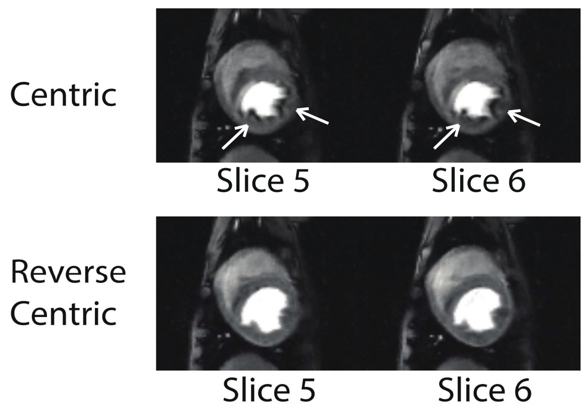

FIG 2: In vivo result shows the dark rim artifacts (white arrows) in the centric order acquisition (top row) for two slices near the middle of the slab. The bottom row is the reverse-centric order, in a time frame adjacent to that in the top row. The reverse-centric doesn't show dark rim artifact in this study.

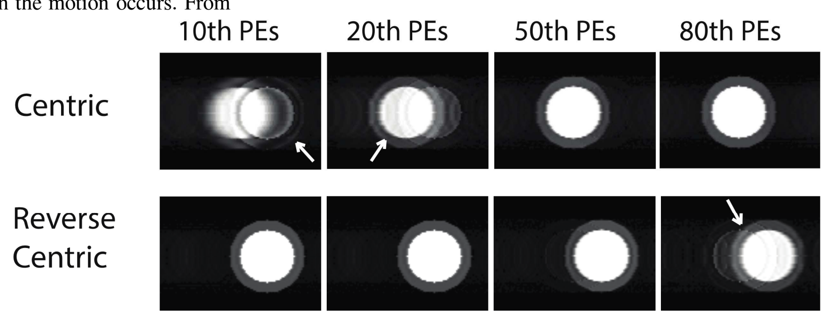

FIG 3: Center slice taken from the 3D simulation, the result shows the artifacts due to the motion along the phase encode direction at different points in one time frame. Strong artifacts appear with the centric order (row 1 first two with arrow) when the motion happens earlier. A similar artifact was observed in the reverse-centric (row 2 last two with arrow) order, when the motion happens close to the end of the 98 phase encodes.

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