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Motion Artifact Suppression in Breath Hold 3D Contrast Enhanced Magnetic Resonance Angiography using ECG Ordering

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***Abstract*—Vascular pulsation and cardiac motion compromise image quality in contrast enhanced magnetic resonance angiography (CE-MRA) in the thorax, resulting in blurring and ghosting artifacts. The use of ECG gating has been proposed in the past to mitigate these artifacts but previous methods suffered from increased scanner time because only a fraction of the cardiac cycle was used for image acquisition and from loss of the study when gating failed. We propose a robust ECG ordering of k-space for breath hold CE-MRA that acquires the central part of k-space in a motion-free portion of diastole and fills in from the periphery of k-space at all other times. To make maximal use of the contrast enhancement, data is acquired continuously even when the ECG signal is lost. The proposed sequence is shown to allow thoracic and pulmonary MRA with a higher resolution when compared to the conventional gated sequence.**

I. Introduction

Contrast enhanced magnetic resonance angiography (CE-MRA) allows a high resolution three dimensional depiction of the vasculature [1]. In the thorax, image quality may suffer from respiratory and cardiac motion and vascular pulsation. They have the potential to cause major ghosting and blurring artifacts, limiting the clinical usefulness of this technique.

Respiratory motion is counteracted by instructing patients to hold their breath. Suppressing vascular pulsation artifacts relies on ECG triggering or gating. Restricting data acquisition to a cardiac phase specific window has been proposed for time-of-flight magnetic resonance angiography (TOF-MRA) in the lower extremities [2] and for phase contrast magnetic resonance angiography (PC-MRA) of carotid artery disease [3]. Systolic (maximizing inflow) or diastolic (minimizing motion) cardiac phases were used as acquisition windows. To reduce the unavoidable lengthening of scan times, gating was restricted to views within a certain region in *k*-space, mostly the central part [4].

The use of ECG triggering or gating has been extended to contrast enhanced MRA [5]. Typically, for a Cartesian acquisition matrix, all phase encodings for a fixed slice encoding are acquired in a single window within one cardiac interval using linear view ordering, which limits the possible number of phase encodings. The central slice encodings are acquired halfway through the scan. This technique has been used to evaluate coronary artery bypass graft patency [6-8] and thoracic abnormalities [9]. Because these techniques use only a portion of the cardiac cycle, they increase scan time and do not make maximal use of the contrast bolus.

In this work, we introduce a robust ECG ordering for contrast enhanced MRA of the thoracic vasculature without increasing scan time. ECG signal is monitored in real time. The central *k*-space views are acquired only in the mid-diastolic rest period of the cardiac cycle [10]. Peripheral views are acquired at any other time, allowing continuous data acquisition. This ECG ordering technique allows a more flexible acquisition matrix, is robust against ECG signal imperfections and, when compared to the conventional technique, allows a higher resolution within the same scan time.

II. Materials and Methods

The standard SPGR sequence on the scanner was modified to allow continuous monitoring of the ECG signal without interruption of the data acquisition. The *k*-space view table (having N views) was split into a central and a peripheral part. The size of the central part of *k*-space was equal to $N_{RP} \times N_{CI}$, where N_{RP} is the number of TRs that fit in the rest period prescribed by the user and N_{CI} is the expected number of cardiac intervals (total scan time divided by the length of the cardiac interval). The central view table was reordered according to a recessed elliptical centric view with the views closest to the center of *k*-space shifted to a position equal to $T_{REC} \times N_{RP}$, where T_{REC} is the index of the heart beat in which the absolute center of *k*-space was to be acquired (prescribed by the user). Recessed elliptical view ordering has been shown to suppress motion artifacts and decrease timing error dependence [11, 12].

The peripheral part of k-space is divided into two sections, one containing all views with high k_z and one containing views with low k_z (see Fig. 1a). During scanning, views acquired before the rest period in the cardiac cycle were taken from the first section, while those after the rest

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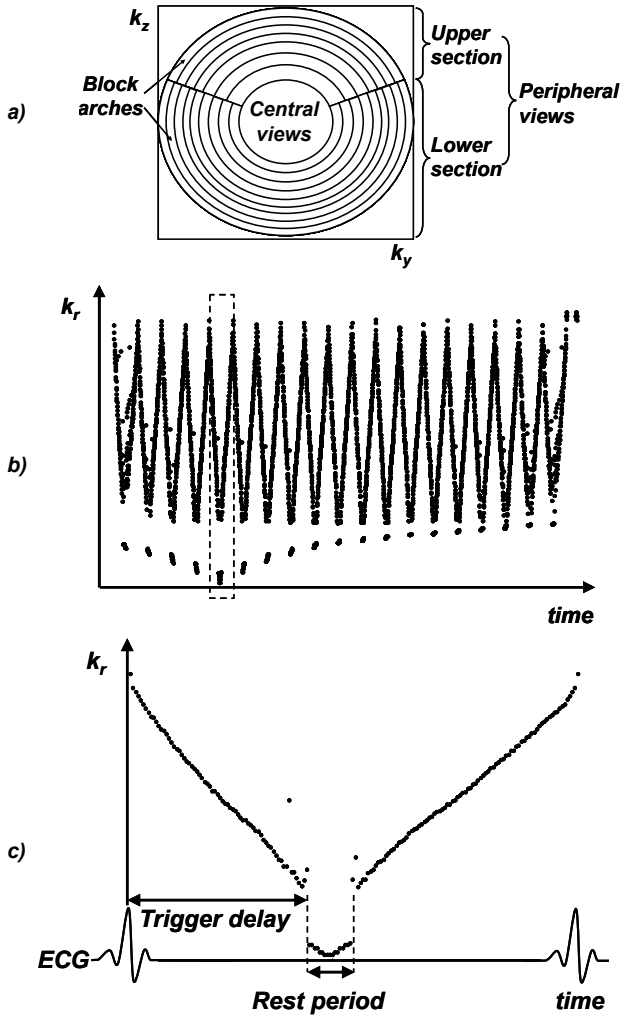

Fig. 1. ECG ordered MRA. The ECG ordering is determined by three parameters: the trigger delay between the ECG trigger and the mid diastolic period of minimal cardiac motion, the length of this period and the recess time for the recessed elliptical centric view ordering. Central *k*-space views are acquired only within this mid-diastolic period. a) partitioning of *k*-space (see text) b) k_r versus time plot for whole scan c) k_r versus time plot for the fifth heart beat.

period came from the second section. The sizes of these two sections were adjusted according to the prescribed trigger delay and heart rate. Each of these outer sections was divided further into block arches containing N_{CI} views that have a similar *k*-space radius (see Fig. 1a). When not scanning during the rest period, the sequence traverses the arches from the first section (outer towards inner arches) before the rest period and traverses the arches from the second section (inner back to outer arches) after the rest period. When scanning during the rest period, the sequence acquires the next available view in the central view table. This way, the sequence induced an effective recessed elliptical view order in each cardiac interval such that views closer to the center of *k*-space are acquired closer to the rest period. Views from the central view table were acquired only within that rest period. This edge-center-edge view order has been shown to be most effective in suppressing motion artifacts [15]. Data acquisition was never interrupted and, as a consequence, the sequence made maximal use of the contrast bolus. Fig. 1b-c shows a plot of the *k*-space radius $k_r = \sqrt{k_y^2 + k_z^2}$ versus time in ECG ordered MRA.

When at any given time, the sequence needed to choose from a particular arch that was completely acquired, it searched for a yet unacquired view in any of the arches (within the same section) further away from the *k*-space center. When this was not possible, disdacqs were played out. This case might arise when during the scan the heart rate significantly drops. When, due to ECG signal loss or other ECG irregularities, no trigger was detected for a period equal to a three cardiac cycles, ECG signal tracking was turned off. The sequence then acquired all remaining views, starting from the most central remaining one and ending with the edge of *k*-space, in effect producing an elliptical centric view order. Additionally, the sequence also detected when it did not traverse the center of *k*-space often enough. This could be caused by both a sharp increase and decrease in heart rate. When this abnormality was detected, ECG signal tracking would be turned off as well and the scan would finish regardless of ECG signal quality.

In order to evaluate the effectiveness of the ECG ordered sequence, it was compared to the sequentially ordered cardiac gated product pulse sequence on the scanner. This sequence acquired all phase encodings for a given slice encoding in one heartbeat and played out disdacqs until the next ECG trigger, at which point all phase encodings for the next slice encoding were acquired. Simulations of these two view orders were performed assuming (i) a constant heart rate of 60 beats per minute and (ii) a 100 ms rest period after a 400 ms delay. Gray scale plots were constructed to visualize the time within the cardiac interval when a view was acquired. Imaging parameters used for these simulations were TR/TE = 6.3/1.2 ms, 192 phase encodings with 70% phase FOV and 30 slice encodings for both view orderings.

Experiments were performed on a GE Excite 1.5T scanner (GE Healthcare, Waukesha, WI). Before the contrast enhanced MRA, an axial cine SSFP scan through the heart was performed to determine the ECG trigger delay and the length of the rest period. Scanning parameters were: 32 cm FOV, 65%-0.80% phase FOV, 256x160x38-46 acquisition matrix interpolated to a 512x512x76-92 image matrix, TR = 3.1 ms, TE = 0.8 ms, and slice thickness 3 mm. An axial slab was placed in the thorax center centered on the heart. For contrast enhancement, 15-20cc of Magnevist (Berlex Laboratories, Wayne, NJ) was injected immediately before scanning. The subject was instructed to hold his breath during the 18-21 seconds scan time. This scan was repeated 10 to 15 seconds later.

Six healthy volunteers and seven patients with confirmed cardiac disease were enrolled in our study. For every volunteer, two injections were performed ten to fifteen minutes apart, one followed by the proposed ECG ordered scan and one followed by the conventional sequentially

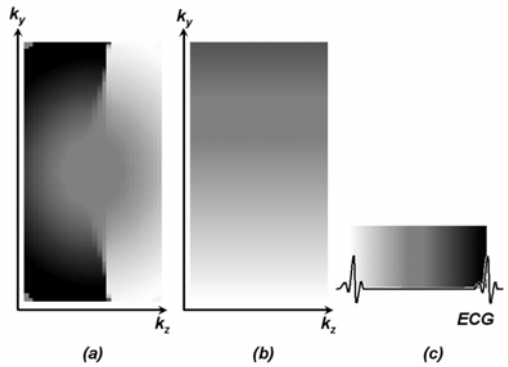

Fig. 2. *k*-space plots for a) ECG ordering and b) sequentially ordered gating. The horizontal axis represents slice (k_z) encoding while the vertical axis indicates phase (k_y) encoding. Each view is colored according to the time in the cardiac interval at which it is acquired (c). The plot in (a) corresponds to the k_r versus time plot in Fig. 1.

ordered cardiac gated scan. Their order was randomized for each participant. The scanning parameters for the sequentially ordered cardiac gated scan were identical (including trigger delay) except for the number of slices (reduced to 18-20) and the slice thickness (increased to 6mm). This was done to obtain the same volumetric coverage within the same acceptable breath hold time (up to 21 seconds depending on heart rate.)

III. Results

Fig. 2 shows the *k*-space for ECG ordering (a) and sequential gated ordering (b). The position of each view within the cardiac cycle is color-coded: white (beginning of cardiac cycle) over gray (rest period) to black (end of rest period) (Fig. 2c.) Both view orders perform a smooth mapping of *k*-space views onto the space of cardiac phases.

Fig. 3 shows images acquired in a 32 year old male volunteer using the ECG ordered sequence. While the scan time (20 sec) and volumetric coverage remained the same, the ECG ordered scan doubled the slice resolution: voxel size went from 2x2x6 mm for the conventional cardiac gated scan to 2x2x3 mm for the ECG ordered scan. (reconstructed to 1x1x3 mm and 1x1x1.5 mm, respectively). Fig. 3b-d shows that this reduction allows the reformatting of images into arbitrary planes.

IV. Discussion and Conclusion

The preliminary data in this study showed that ECG ordered contrast enhanced magnetic resonance angiography is successful in suppressing ghosting artifacts caused by vascular pulsation and in reducing blurring artifacts associated with heart motion. In this technique, image data are acquired continuously, as opposed to the sequentially ordered gated sequence. The central region of *k*-space is acquired only during the period of minimal motion in the cardiac cycle. ECG triggering is implemented with a fail proof algorithm that defaults to continuous elliptical centric data collection when the ECG signal is lost. This technique may be particularly important for performing high quality high resolution thoracic MRA including the depiction of pulmonary vasculature.

ECG triggering for CE-MRA has been recognized [5]. A drawback of older techniques is that data is acquired only during a fixed portion of the cardiac cycle. In the case of first pass contrast enhanced MRA, it is highly desirable to scan continuously. This is especially the case in thoracic and cardiac contrast enhanced MRA, where a breath hold is necessary. Additionally, the proposed sequence uses a recessed elliptical-centric view ordering [11]. In older techniques, all phase encodings for a given slice encoding were acquired sequentially within the same cardiac interval. In the proposed technique, the length of the expected cardiac interval, which can be quite short for a high heart rate, does not impose any limitations on the acquisition matrix. Moreover, the recessed elliptical-centric view ordering has been shown to suppress motion artifacts and to be less susceptible to timing related errors. A third difference with older techniques is the presence of a built-in failsafe that makes sure that the sequence finishes scanning without an unreasonable extension of scan time (e.g. following a sharp increase in heart rate). It will also finish and produce images when the ECG signal is lost, a condition that causes the current ECG triggered sequence on our scanner to fail, resulting in lost scanning time and contrast material.

Residual motion remains in the periphery of *k*-space (Fig. 2a.), degrading finer details in the image [13]. Combined with the thin slices used in this study, this resulted in increased residual motion artifacts visible in the images. Previous studies have indicated that minimizing motion in the *k*-space center is an effective strategy to reduce motion artifacts for both large and small structures because the majority of their signal is located at the *k*-space center [4, 10, 14-16]. Accordingly, in the situation of limited scan time, the ECG ordering technique forms an effective approach to reducing motion artifacts.

Compared to the conventional sequentially ordered cardiac gated sequence, ECG ordered scans offers the advantage of imaging the entire heart and the aortic root in an axial slab with relatively thin slices (3 mm was used in this study). This is especially useful for reformatting of the resulting axial views into arbitrary view planes. Moreover, total scan time is not dependent on heart rate. Finally, this sequence is more robust against ECG signal abnormalities. In one of the volunteers, ECG triggers were missed during the first five heart beats of the scan. Nevertheless, the scan finished using an elliptical centric view ordering.

In conclusion, we have presented an ECG ordering for contrast enhanced thoracic magnetic resonance angiography, which combines the advantages of fast continuous scanning, recessed elliptical-centric view ordering and cardiac phase specific acquisition of the central part of *k*-space. It is shown to suppress major ghosting and blurring artifacts caused by vascular pulsation and cardiac motion and does so without limiting the acquisition matrix or prolonging scan time. Compared to the conventional gated technique, it

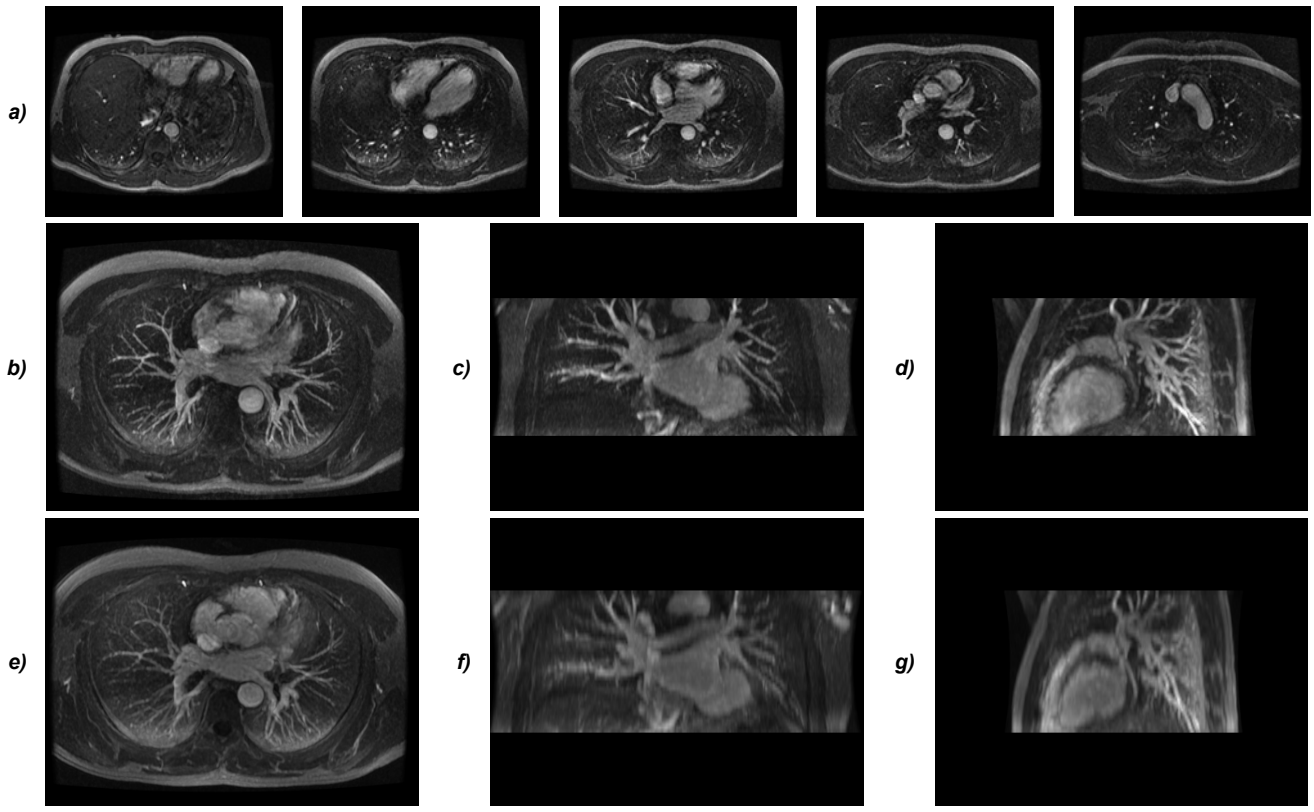

Fig. 3. a) Source images from an ECG ordered contrast enhanced MRA in a 32y old volunteer. Not all slices are shown. They demonstrate the coverage of the whole heart, pulmonary arteries and veins and aortic root. A smaller slice thickness allows better reformatting of the axial images into arbitrary view planes: axial (b), coronal (c) and sagital(c). Acquired voxel size is 2x2x3 mm reconstructed to 1x1x1.5 mm. Images in (e-g) show the corresponding reformatted MIP images using the conventional sequentially ordered sequence. The decreased slice resolution manifests itself in blurred sagittal and coronal reformatted images. Acquired voxel size here is 2x2x6 mm reconstructed to 1x1x3 mm.

allows a higher resolution depiction of thoracic and pulmonary vasculature with adequate volumetric coverage in essentially the same scan time.

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