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Technical note

Beat-to-beat respiratory motion correction with near 100% efficiency: a quantitative assessment using high-resolution coronary artery imaging☆

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Abstract

This study quantitatively assesses the effectiveness of retrospective beat-to-beat respiratory motion correction (B2B-RMC) at near 100% efficiency using high-resolution coronary artery imaging. Three-dimensional (3D) spiral images were obtained in a coronary respiratory motion phantom with B2B-RMC and navigator gating. In vivo, targeted 3D coronary imaging was performed in 10 healthy subjects using B2B-RMC spiral and navigator gated balanced steady-state free-precession (nav-bSSFP) techniques. Vessel diameter and sharpness in proximal and mid arteries were used as a measure of respiratory motion compensation effectiveness and compared between techniques. Phantom acquisitions with B2B-RMC were sharper than those acquired with navigator gating (B2B-RMC vs. navigator gating: 1.01±0.02 mm^{-1} vs. 0.86±0.08 mm^{-1}, P<.05). In vivo B2B-RMC respiratory efficiency was significantly and substantially higher (99.7%±0.5%) than nav-bSSFP (44.0%±8.9%, P<.0001). Proximal and mid vessel sharpnesses were similar (B2B-RMC vs. nav-bSSFP, proximal: 1.00±0.14 mm^{-1} vs. 1.08±0.11 mm^{-1}, mid: 1.01±0.11 mm^{-1} vs. 1.05±0.12 mm^{-1}; both P=not significant [ns]). Mid vessel diameters were not significantly different (2.85±0.39 mm vs. 2.80±0.35 mm, P=ns), but proximal B2B-RMC diameters were slightly higher (2.85±0.38 mm vs. 2.70±0.34 mm, P<.05), possibly due to contrast differences. The respiratory efficiency of B2B-RMC is less variable and significantly higher than navigator gating. Phantom and in vivo vessel sharpness and diameter values suggest that respiratory motion compensation is equally effective.
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1. Introduction

For high-resolution applications, the majority of cardiovascular magnetic resonance studies are performed with respiratory gating during free-breathing using diaphragmatic navigators [1,2]. The accept/reject algorithm [3,4], used to limit respiratory motion to a small (typically 5 mm) gating window around end expiration, is inherently inefficient and unpredictable particularly in the presence of respiratory drift [5]. A number of techniques including motion adaptive gating [6] and phase encode ordering methods [7–9] reduce the effects of respiratory motion within the navigator acceptance window, enabling improved image quality or greater respiratory efficiency. Alternatively, navigator information may be used to both gate and provide input to respiratory motion models which relate the motion of the diaphragm to that of the heart. The most basic of these models uses a fixed superior–inferior factor to perform slice tracking [1,10], but tracking factors vary considerably between subjects [11,12], and calculating accurate subject-specific values is both difficult and time consuming. More complex models, often derived from multiple navigators, include three-dimensional (3D) translational [13] and affine transformations [14–16] which take into account the nonrigid deformation of the heart and its hysteretic relationship with the diaphragm. Such methods have enabled increases in the acceptance window from 5 to 10 mm without loss of image quality, resulting in improved respiratory efficiency (from ~40% [4] to ~70% [17]). These models, however, are derived from a prescan and do not adapt to

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changes that may occur over subsequent long acquisitions. Several novel non-model-based alternatives have been developed which derive respiratory motion information directly from the anatomy of interest. Self-gated techniques use respiratory information obtained from a repeated superior–inferior projection within the acquisition to gate [18] or perform one-dimensional translational corrections [19], while other methods reconstruct heavily aliased subimages from a subset of the full high-resolution acquisition on every cardiac cycle for respiratory gating [20] or to obtain 3D affine corrections [21]. Alternatively, simultaneously acquired additional low-resolution images have been used to obtain two-dimensional (2D) in-plane translational corrections [22] and rotations [23].

Recently, a beat-to-beat respiratory motion correction (B2B-RMC) technique [24] was developed whereby unaliased 3D low-resolution images of the epicardial fat surrounding the heart are acquired on every cardiac cycle. The low-resolution fat images from each cardiac cycle are used to derive beat-to-beat 3D localized translations for the coronary arteries. The motion information obtained is used to correct the corresponding 3D high-resolution data acquired immediately afterwards in the same cardiac cycle. This technique was initially [24] demonstrated for black blood 3D spiral right coronary artery wall imaging with 100% respiratory efficiency. In this manuscript, we present the first quantitative assessment of the efficacy of this motion correction technique. Three-dimensional high-resolution imaging of the right coronary artery was chosen as the imaging application as its small size and substantial motion with both the cardiac and respiratory cycles make it a particularly challenging target. The efficacy of the technique is verified with comparison to an identical navigator gated sequence in 3D spiral acquisitions of a coronary artery test object moving with realistic respiratory motion. Subsequently, a full in vivo evaluation in 10 healthy subjects comparing 3D spiral imaging using B2B-RMC to a widely used navigator-gated coronary artery imaging technique is presented.

2. Methods

All imaging was performed on a Siemens 1.5 T Avanto MRI scanner (Siemens Medical Systems, Erlangen, Germany) with maximum gradient amplitude 40 mT/m and maximum slew rate 170 mT/m/s, using an anterior phased array coil. In vivo acquisitions were gated using an electrocardiographic system which was designed in-house.

2.1. Phantom acquisitions

A test object was constructed to imitate the proximal and mid right coronary artery surrounded by epicardial fat in the atrioventricular groove. This was achieved, as shown in Fig. 1, by positioning a curved water-filled straw (diameter 3 mm) in a V-shaped groove in a wax block and surrounding the straw with fat (lard). Air bubbles within the straw

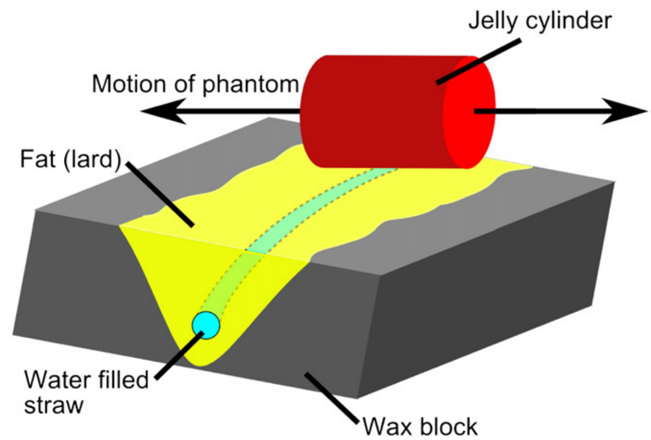

Fig. 1. The coronary artery test object consisted of a water-filled straw within a fat-filled groove in a wax block which was rotated with respect to the direction of motion. A jelly-filled cylinder was placed adjacent to the test object and orientated parallel to the direction of motion in order to monitor the phantom location with a standard navigator.

provided additional structural detail for visual assessment of the effects of motion. A gel cylinder was placed adjacent to the coronary artery test object and was used for monitoring displacement with a standard navigator [2]. Both objects were placed on the trolley of a mechanical respiratory motion phantom, driven by a stepper motor system with microstepping capabilities. The phantom was programmed to follow respiratory traces obtained from six healthy subjects using a diaphragmatic navigator (repeat time [TR]=250 ms, acquisition duration=~5 min). The first five respiratory traces had mean amplitudes in the range 8–17 mm and mean respiratory periods in the range 3–6 s. The sixth volunteer had a respiratory trace with an unusually large amplitude (36 mm) and long mean period (11 s). The test object was orientated so that motion along the axis of the magnet bore resulted in translation (without deformation) of the vessel test object both in and through the imaging plane which was orientated in the plane of the vessel. Imaging of the phantom was performed using a 3D spiral acquisition, as described below. Three acquisitions were performed: (a) with no motion, (b) with motion (reconstructed with and without B2B-RMC) and (c) with motion and a standard navigator accept/reject algorithm (5-mm window). In this way, the performance of B2B-RMC is directly compared to accept/reject navigator gating and motion free acquisitions using an identical sequence.

2.2. In vivo acquisitions

A right coronary artery imaging protocol was performed on 10 healthy subjects (5 female, 22–53 years old) recruited with informed consent according to local ethics procedures. The longest right coronary rest period was first determined from a cine acquisition in a plane showing the four-chamber view [25]. All subsequent high-resolution imaging was performed in this rest period. In-plane high-resolution right

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