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MR coronary artery imaging with 3D motion adapted gating (MAG) in comparison to a standard prospective navigator technique

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Magnetic resonance coronary angiography (MRCA) has been proven to be feasible for imaging of the proximal and medial portions of the three main coronary arteries. Free breathing techniques allow for high resolution imaging but prolong scan time. This could potentially be shortened by improving the efficiency, robustness and accuracy of the navigator gating algorithm. Aim of this study was to determine the feasibility, efficiency, and image quality of a new motion compensation algorithm (3D-MAG) for coronary artery imaging with navigator techniques. In 21 patients the coronaries were imaged in plane with a 3D k-space segmented gradient echo sequence. A T2 preparation prepulse was used for suppression of myocardial signal, during free breathing and a navigator technique with using real time slice following and a gating window of 5 mm was applied to suppress breathing motion artefacts. Imaging was performed with standard gating and compared to 3D-MAG. Image quality was visually compared, contrast-to-noise and signal-to-noise ratio were calculated, the length of visualized coronary arteries was measured and scan duration and scan efficiency were calculated. Standard navigator imaging was feasible in 19 of 21 (90.5%) patients 3D-MAG in 21/21 (100%). Scan efficiency and duration was significantly improved with 3D-MAG ($p < .05$) without change in image quality. 3D-MAG is superior to conventional navigator correction algorithms. It improves feasibility and scan efficiency without reduction of image quality. This approach should be routinely used for MR coronary artery imaging with navigator techniques.

Key Words: Magnetic resonance imaging; Coronary angiography; Motion suppression; Breathing motion

1. Introduction

Magnetic resonance coronary angiography (MRCA) has been proven to be feasible for imaging of the proximal and medial portions of the three main coronary arteries. The techniques have been continuously improved from 2D time of flight techniques (1–3) to 3D techniques with breath holding or respiratory triggering, which can be combined with real-time adaptation of diaphragmatic displacement (4, 5). Improved contrast-to-noise ratio has been achieved by the application of T2 suppression pulses (6). Recently results from a first multicenter trial using a standardized navigator technique with T2 preparation pulses were reported with 84% evaluable segments, a sensitivity of 93% and a specificity of 42% for the detection of > 50% stenosis (7). The major limitation of high resolution navigator MR coronary artery imaging is the extensive scan time. Improving the efficiency, robustness and accuracy of the navigator gating algorithm could help to solve these problems. Improved efficiency would lead to a reduction of scan time, increased robustness would allow to use this technique in more patients and better accuracy would lead to an improvement of image quality, due to a reduction of blurring. Aim of this study was to determine the feasibility, efficiency, and image quality of a new motion compensation algorithm (3D-MAG) for coronary artery imaging with navigator techniques.

2. Methods

2.1. *Patients*

Twenty-one patients were included into the study after written informed consent. Exclusion criteria were coronary stents, cardiac arrhythmias or contraindications to MR (incompatible metal, claustrophobia).

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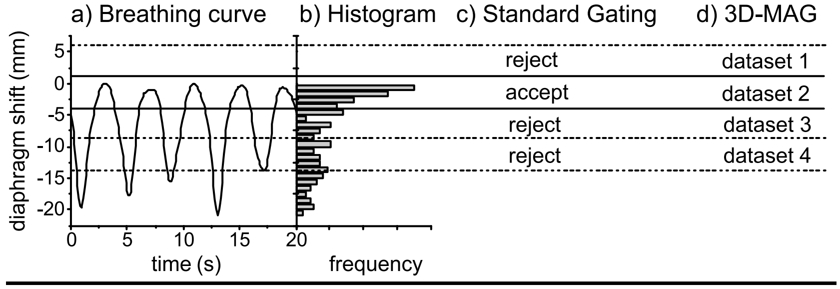

Figure 1. Breathing curve (a) and corresponding histogram of motion states (b). In standard gating (c) an accept/reject decision is made with respect to a fixed gating window (solid lines). 3D-MAG completes a full dataset from a variety of different diaphragmatic positions.

2.2. *3D navigator imaging*

All patients were examined in supine position using a 1.5 Tesla ACS NT scanner (Philips, Best, The Netherlands) equipped with 23 mT/m amplitude, 219 μs rise time gradients. A 5 element specific cardiac phased array coil was placed around the thorax of the patients. After a rapid survey with transverse, sagittal and coronal views, the dome of the right diaphragm and the proximal parts of the left main and right coronary artery were localized. The coronaries were imaged in plane with a 3D k-space segmented gradient echo sequence using a T2 preparation prepulse for suppression of myocardial signal (6) using a previously described three-point plan scan tool (8). The navigator beam was placed on the dome of the right diaphragm. In consideration of the heart rate measured during the examination, images were acquired in mid-diastole (9) using an acquisition window of 80 ms. Images were acquired during free breathing using a navigator technique with real time slice following and a gating window of 5 mm to suppress breathing motion artifacts. In-plane resolution was 0.7×0.9 mm with a slice thickness of 1.5 mm (FOV = 360 mm). For comparison the sequence were performed both with standard gating and 3D-MAG. To reduce overall examination time, one coronary artery territory (LAD and RCX or RCA) was randomly assigned for imaging. If time permitted, a second territory was additionally imaged.

2.3. *3D-MAG*

3D-MAG is a 3D imaging extension of the multi-level approach PAWS (Phase-ordering with automatic window selection) (10) and automatically selects the optimal respiratory gating window (Fig. 1). A detailed description of the algorithm is found in Fig. 2.

Similar to PAWS, the diaphragmatic displacement range was divided into 9 portions of 2 mm each (= bands). Three consecutive bands form a full 2D phase encoding space. The starting point for data collection (= end-expiraty positon) was determined from a navigator-preparation phase during free breathing. This starting point was used to place the first set of three bands. A scan was finished when 3 consecutive bands were completely filled. In contrast to PAWS, no distinction was made between central k-space and outer k-space regions. Furthermore, a fixed band size (i.e., number of phase encoding steps) was used. This allows a more flexible and robust implementation with respect to different 3D-k-space segmentation schemes. Once a band is completed, the neighboring bands are filled according to a special strategy, which minimizes scan time without broadening the effective gating window. This is demonstrated in detail in Fig. 2. Initial experiments indicated that 9 bands are sufficient to cope with drifts (total possible displacement 18 mm).

2.4. *Analysis*

Image quality was visually compared for the two scanning techniques on a 3-point scale by three independent observers blinded to the acquisition technique: 1 = image quality inferior; 2 = image quality identical; 3 = image quality superior.

Signal intensity (SI) from blood was determined in the ascending aorta (mean value) and from muscle in the left

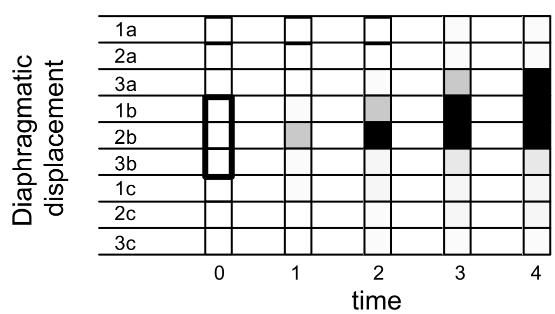

Figure 2. The diaphramatic displacement range is divided into 9 bands (1a–3c). Three consecutive bands form one complete dataset (e.g. 1b-2b-3b, 3a-1b-2b, 2b-3b-1c etc.). Initially (time point 0) the central band (2b) is placed on the expected optimal position, as determined from a prescan. The range 1b–3b forms the expected full dataset. During scanning, data is stored in each of the bands depending on diaphragmatic position (demonstrated as increasing grey shading). Once a band is completed (e.g., band 2b at time point 2), the diaphragmatic position formerly used to fill this band is now used to fill the neighboring band belonging to the most advanced triple of neighboring bands (e.g., 1b). Once this is achieved (e.g., 1b at time point 3), both diaphragmatic positions (1b and 2b) "help" to fill in the remaining third (e.g., band 3a). When three neighboring bands are filled, the scan is completed (time point 4).

Table 1. Image quality

	3D-MAG vs. conventional navigator			
Observer	I	II	III A	III B
Mean	2.05 ± 0.73	1.83 ± 0.71	2.0 ± 0.84	2.22 ± 0.81
Mean value (all observers)		2.02 ± 0.75		

I, II and III represent different observers. IIIA and IIIB represent different reads of observer III.
1 = Conventional navigator superior to 3D-MAG; 2 = Image quality identical; 3 = 3D-MAG superior to conventional navigator. Differences not significant.

ventricular myocardium (mean value). Background noise was measured in an artifact free area of air (standard deviation). Contrast-to-noise ratio was calculated as: SI blood – SI muscle/noise. Signal-to-noise-ratio was calculated as: SI blood/noise.

The length of visualized coronary arteries was measured. Scan duration and scan efficiency were calculated. Mean values ± SD of all parameters are given. Comparisons between conventional and 3D-MAG imaging were performed with a paired *t*-test. A p value of $< .05$ was regarded as statistically significant.

3. Results

3.1. *Feasibility*

Standard navigator imaging was feasible in 19 of 21 (90.5%) patients (17 LAD/RCX, 12 RCA). In 2 patients low scan

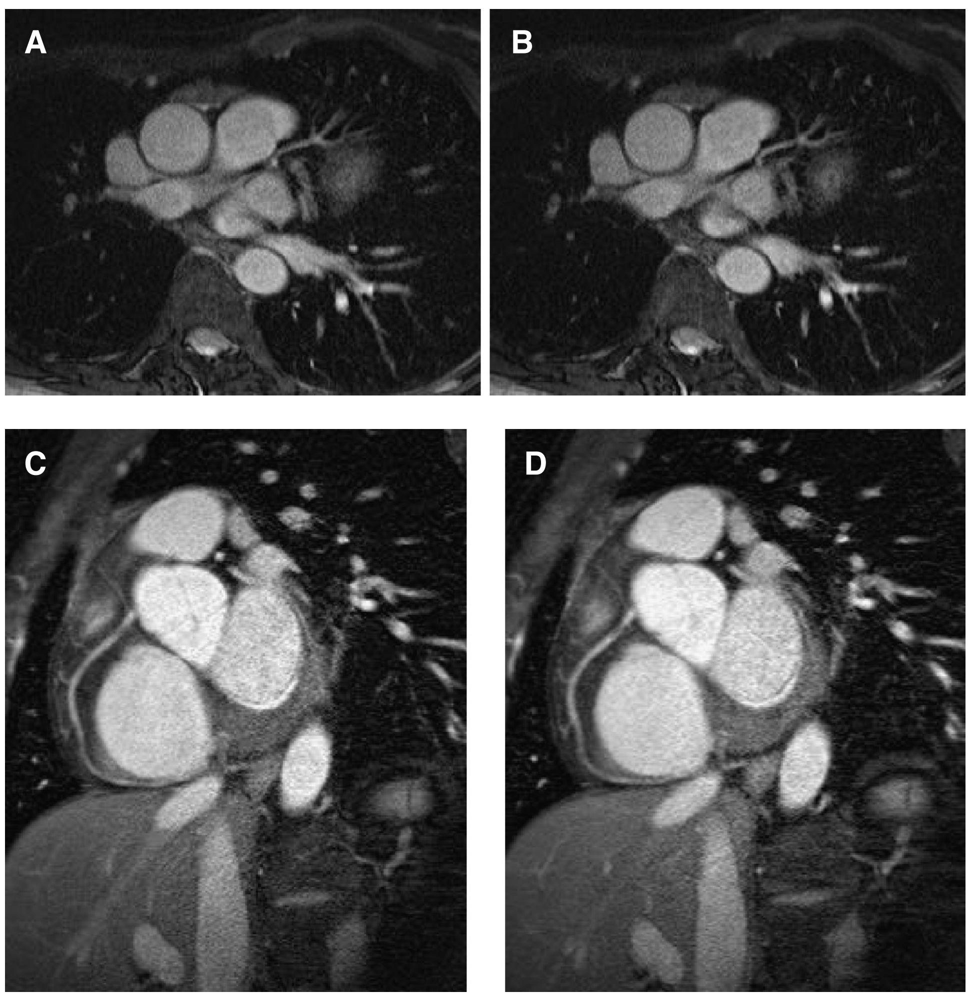

Figure 3. Examples of coronary artery images acquired without (left; A + C) and with (right; B + D) 3D-MAG. No significant difference in image quality was found.

Table 2. Signal (SNR) and contrast to noise ratio (CNR) for conventional navigator and 3D-MAG

	Conventional navigator	3D-MAG	p value
LAD (visible vessel length) [mm]	54 ± 26	64 ± 31	NS
RCX (visible vessel length) [mm]	37 ± 12	35 ± 12	NS
RCA (visible vessel length) [mm]	85 ± 45	85 ± 37	NS
SNR	37.1 ± 12.6	38.4 ± 11.8	NS
CNR	21.1 ± 9.0	23.2 ± 8.5	NS

NS = Not significant.

efficiency did not allow to complete data acquisition. With 3D-MAG all patients could be completed.

3.2. *Acquisition efficiency*

Scan efficiency was 46 ± 16% (11–82%) for the conventional approach and 54 ± 15% (34–97%) for the 3D-MAG approach ($p < .02$). Scan duration was 14.4 (SD 7.87) minutes for conventional navigator and 11.1 (SD 2.35) minutes for 3D-MAG ($p < .05$).

3.3. *Image quality*

The results for image quality are listed in Table 1. Examples are shown in Fig. 3.

3.4. *Quantitative evaluation*

Visibile vessel length between the two techniques did not differ for the differenttechniques (Table 2).

Contrast-to-noise and signal-to-noise ratio are tabulated in Table 2.

4. Discussion

The use of an optimized navigator algorithm for reduction of breathing motion artifacts during MR coronary artery imaging (3D-MAG) yields identical image quality in shorter scan times compared to conventional navigator imaging. A higher number of patients could be imaged with 3D-MAG in comparison to the conventional navigator approach, which failed in 10% of the patients. In addition, navigator efficiency was increased significantly from 46% to 54% leading to a reduction of scan time. Image quality remained unchanged. Thus, 3D-MAG improves robustness and efficiency of MR coronary angiography without drawbacks in quality and should be used routinely.

The advantage of PAWS (and thus 3D-MAG) compared to other advanced gating techniques such as the diminishing variance algorithm (DVA) (11) is that for a given gating window width the scan is always completed in minimum scan time. On the other hand, no image can be reconstructed before completion of the scan, in contrast to the DVA approach.

In some patients with complex and unfavorable breathing patterns (e.g., strong diaphragmatic drifts) conventional navigator approaches result in very long scan times, due to a low efficiency.

In some of these patients, efficiency is reduced to an extent, which prohibits completion of the scan. Several approaches like T2 suppression pulses, T2 preparation an fat suppression pulses, multiple breath hold imaging method, two step navigatorless correction and any other have been suggested to solve this problem.

Importantly, image quality remained unchanged in the current study. Thus, this approach can be used routinely in MR coronary angiography. The higher efficiency and resulting shorter scan times may be used to increase signal to noise ratio, e.g., by applying a higher number of signal averages.

4.1. *Limitations*

In the current study image quality was compared between two methods rather than determining absolute image quality. Whereas this approach does not allow comparing the results from this study to other publications, a better comparison between the two approaches is possible, since individual determinants of image quality (e.g., breathing pattern, cardiac motion, etc.) do not influence the results. More, absolute parameters of image quality are visible length of the coronary arteries and the ratio of signal and contrast to noise ratio. These values are within the range of previous studies using similar techniques.

Since no clinical reference standard (invasive angiography) was available, this study does not approach the diagnostic accuracy of the technique used but focuses on the feasibility and image quality effects of an improved navigator algorithm. Future studies should evaluate the influence on diagnostic performance.

5. Conclusions

3D-MAG yields identical image quality to conventional navigator correction algorithms while imaging time is reduced and feasibility increased. This approach should be routinely used for MR coronary artery imaging with navigator techniques used for the suppression of breathing motion artefacts.

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