Journal of Cardiovascular Magnetic Resonance (2006) **8,** 703–707

ISSN: 1097-6647 print / 1532-429X online
DOI: 10.1080/10976640600723706

informa
healthcare

Coronary Artery Magnetic Resonance Angiography (MRA): A Comparison between the Whole-Heart and Volume-Targeted Methods Using a T_2-Prepared SSFP Sequence

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ABSTRACT

In this study, coronary MRA was performed on 10 healthy volunteers using the whole-heart and volume-targeted scans with comparable imaging parameters. Similar results in the SNR, CNR, and vessel diameter were observed. The depicted length of coronary arteries was longer using the whole-heart scan (whole-heart: RCA/LAD = 13.4 ± 3.9/10.5 ± 1.6 cm; volume-targeted: RCA/LAD = 11.0 ± 2.6/8.7 ± 1.8 cm). Imaging times for the RCA- (3.8 ± 1.4 minutes) and LAD-targeted (3.6 ± 1.3 minutes) are similar, while the time required for one whole-heart scan is significantly longer (12.2 ± 4.0 minutes). The measured vessel sharpness was higher using the volume-targeted method (whole-heart: RCA/LAD = 0.65 ± 0.18/0.78 ± 0.16; volume-targeted: RCA/LAD = 0.84 ± 0.22/0.90 ± 0.20). Combination of the whole-heart and volume-targeted methods could be potentially useful in clinical applications of coronary MRA.

INTRODUCTION

Volume-targeted imaging has been widely used in magnetic resonance angiography (MRA) of coronary arteries in the past decade (1–4). With such a method, major branches of coronary arteries, including the right coronary artery (RCA), left anterior descending (LAD), and left circumflex (LCX) coronary arteries, are depicted by acquiring several oblique, volumetric, three-dimensional (3D) thin slabs. High quality coronary artery images with sub-millimeter spatial resolution can be acquired with appropriate gating of the cardiac and respiratory motions. However, one of the major limitations for the volume-targeted method is the limited spatial coverage in the slice direction. Sometimes one 3D slab may not be adequate to cover both the proximal and distal portions of a tortuous coronary artery. In addition, planning of the imaging orientation for each coronary vessel relies on the skill of the operator. The scan planning can be time consuming, or even worse, failed in some cases.

Recent advances in imaging techniques especially the successful application of the steady-state free precession (SSFP) sequences in cardiac imaging make it feasible to perform whole-heart imaging with good image quality (5). Typically, a thick 3D slab is collected to cover the whole heart with one single measurement. Images are usually acquired in the transverse plane, which obviously minimizes the load of scan orientation planning. In addition, all major arteries can be visualized by reformatting the collected 3D data set retrospectively. Increase of the spatial coverage can potentially improve the depiction of the coronary artery tree especially those tortuous branches that can hardly be covered by thin slabs in the conventional targeted method. A major drawback of performing whole-heart imaging is the prolonged scan time for each single measurement. As the

Keywords: Magnetic Resonance Angiography (MRA), Coronary Arteries, Steady-State Free Precession, Navigator-Gated, Three-Dimensional.
Received 24 October 2005; accepted 19 February 2006
Supported in part by National Institute of Health grants no. EB002623, HL38698 and Siemens Medical Solutions, Chicago, IL, USA.
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result, alteration of the heart rate and drift of the respiratory motion over an elongated imaging time can jeopardize the efficacy of cardiac and respiratory gating. Furthermore, increased cardiac and respiratory motions can result in blurring of the coronary arteries.

The purpose of this study was to compare the performance of the whole-heart and volume-targeted scans for coronary MRA on healthy subjects using a navigator-gated, electrocardiogram (ECG)-triggered, T2-prepared, fat saturated, segmented 3D SSFP sequence. The resulting signal-to-noise ratio (SNR), contrast-to-noise ratio (CNR), depicted vessel length, diameter, and sharpness using these two acquisition methods were measured and compared.

METHOD

All studies were conducted on a 1.5T whole-body clinical scanner (Avanto, Siemens Medical Solutions, Erlangen, Germany). The scanner is equipped with a built-in whole-body volume coil operating as the radio-frequency (RF) transmitter. The system is capable of operating at a maximum gradient strength of 45 mT/m and a slew rate of 200 mT/m/msec. Signal was collected using a commercial available phased array coil incorporating the Siemens total imaging matrix (TIM) technology. Two anterior channels and two posterior channels close to the heart were turned on for data acquisition.

Ten healthy volunteers (seven males, three females, ages: 24–51 years, mean age: 38.2 ± 10.5 years) without known heart disease were recruited for this study. Written consent was obtained before each experiment in compliance with guidelines of our Institutional Review Board. Subjects were in supine position inside the scanner. Signal from a three-lead wireless ECG system (Siemens Medical Solutions, Erlangen, Germany) was used for gating of the cardiac motions.

Two-dimensional (2D) scout images were first obtained in three orthogonal orientations during free breathing using a low-resolution, segmented SSFP sequence. These scout images were used to help determine the position of the heart and diaphragm. In order to collect coronary MRA data during the relatively quiescent period of each heartbeat, which usually occurred in the mid-diastole, the motions of coronary arteries in one cardiac cycle were observed using a cine scan. The cine images were acquired in the transverse plane for simplicity. A previous study had shown that the motion of the RCA was more extensive than that of the LAD and LCX (6), thus the motion of the RCA was visually assessed from the acquired images series. Those continuous phases showing minimal motion of the RCA were selected. The trigger delay time and the width of the data acquisition window for the whole-heart and volume-targeted scans were set based on the onset time and duration of the selected phases.

An ECG-triggered, fat saturated, T2-prepared, segmented 3D SSFP sequence was employed for coronary artery imaging using whole-heart and volume-targeted methods. All scans were performed under free breathing of the subjects. Respiratory motion was monitored by acquiring a navigator echo from a 2D beam perpendicular to the right hemi-diaphragm. The width of the window for navigator-gating was 6 mm. The shift of the imaged 3D volume was correlated to the shift of the navigator track point using a prospective real-time adaptive motion correction. A constant (0.6) correction factor was used in superior-inferior direction (7, 8). A 40 msec T2-preparation was played to increase the blood-myocardial contrast (9). Following the T2-preparation, 20 linearly ramping-up dummy pulses were played to reduce the transient signal oscillation before data readout (10). The 3D k-space data were collected using centric order in the phase-encoding direction and linear order in the partition-encoding direction. For whole-heart imaging, 44 transverse slices were acquired and sinc-interpolated into 88 slices of 1.3 mm thickness. Oblique planes for the RCA- and LAD-targeted imaging were determined based on the whole-heart images using a built-in three-point planning tool (11). For each of the volume-targeted scans, 16 slices were collected and interpolated into 32 slices. The spatial resolution for targeted scans was identical to that of the whole-heart scan for each subject. Resulting voxel size ranged from 0.9×0.9 mm^2 to 1.3×1.3 mm^2 with 1.3 mm thickness. The required imaging time for the whole-heart scan was 280 ± 30 accepted heartbeats. Corresponding values for the RCA- and LAD-targeted scans were 117 ± 21 and 116 ± 24 heartbeats, respectively. Other imaging parameters included: TR/TE = 3.7/1.7 mm; flip angle = 90°; lines per heartbeat = 25–33; readout bandwidth = 870 Hz/pixel.

Collected coronary images were reformatted using the software available on the imaging workstation. Mappings with maximum-intensity-projection (MIP) technique as well as volume rendering technique (VRT) were performed to visualize the coronary arteries from the 3D data sets. The blood signal intensity, myocardial signal intensity, and the background noise were measured from raw images for SNR and CNR calculation. The circular region-of-interest (ROI, area $\approx$ 100 mm^2) for measuring the blood signal intensity was placed in the aorta at the level of coronary artery origin. Image noise was estimated to be the standard deviation (SD) of a circular ROI (area $\approx$ 180 mm^2) placed in the background air (12). The myocardial signal intensity was measured from the connective tissue immediately next to the coronary arteries (ROI area $\approx$ 60–80 mm^2). The SNRs of the blood and myocardium were obtained by dividing the mean signal intensity of each tissue region by the image noise. The CNR was calculated by subtracting the SNR of the myocardium from that of the blood. The lengths of depicted coronary arteries, lumen diameter, and vessel sharpness were measured using previously described methods (13).

Quantitative values of all measurement were statistically analyzed and the results were presented as mean $\pm$ standard deviation. Comparisons of the SNR, CNR, depicted vessel length, sharpness, and lumen diameter using the whole-heart and volume-targeted scans were performed using a paired two-sample t-test. A two-tailed p-value smaller than 0.05 was considered statistically significant.

RESULTS

Coronary MRA were successfully performed in all subjects without complications. Major branches of the coronary arteries were well depicted using both the whole-heart and volume-targeted methods. Figure 1 illustrates a set of coronary artery images acquired in one volunteer. The RCA and LAD coronary arteries are clearly visible using whole-heart and targeted imaging protocols. Another set of coronary artery images acquired in a 40-years-old volunteer are shown in Fig. 2. For this subject, the LCX coronary artery is depicted in the LAD-targeted image as well.

Measurement results of the imaging time, depicted coronary artery length, vessel diameter, sharpness, SNR, and CNR from each of the ten subjects are summarized in Table 1. Results for LAD-targeted imaging are not available for subject 2 because the volunteer decided to quit the study during the imaging session. Results show that the imaging time for each targeted measurement varies from 2.0 to 5.7 minutes, with average values being 3.8 ± 1.4 and 3.6 ± 1.3 minutes for the RCA- and LAD-targeted scans, respectively. The average imaging time for the whole-heart measurement in this study is 12.2 ± 4.0 minutes, varying between 7.8 and 20.5 minutes. Note the longest imaging time (20.5 minutes) for single measurement occurs on subject 5, when the navigator efficiency is only 25%.

The statistical results of measurements are summarized in Table 2. The SNR is slightly higher using the whole-heart scan although the difference is not significant between the whole-heart (22.9 ± 8.0), RCA-targeted (18.8 ± 5.9), and LAD-targeted (20.7 ± 7.1) imaging. No significant difference in CNR is observed (whole-heart: 10.9 ± 4.9; RCA-targeted: 12.6 ± 5.6; LAD-targeted: 12.7 ± 6.1). Imaging times for the RCA- (3.8 ± 1.4 minutes) and LAD-targeted (3.6 ± 1.3 minutes) scans are similar, while the time required for the whole-heart scan is significantly longer (12.2 ± 4.0 minutes). The depicted lengths of the coronary arteries are significantly longer using the whole-heart scan (RCA: 13.4 ± 3.9 cm; LAD: 10.5 ± 1.6 cm) than using the volume-targeted method (RCA: 11.0 ± 2.6 cm; LAD: 8.7 ± 1.8 cm). However, the resulting vessel sharpness is higher using targeted method for both the right and LAD coronary arteries. Quantitative results of the sharpness measurement for the RCA are 0.84 ± 0.22 and 0.65 ± 0.18, respectively using targeted and whole-heart methods. Corresponding values for the LAD coronary artery are 0.90 ± 0.20 and 0.78 ± 0.16.

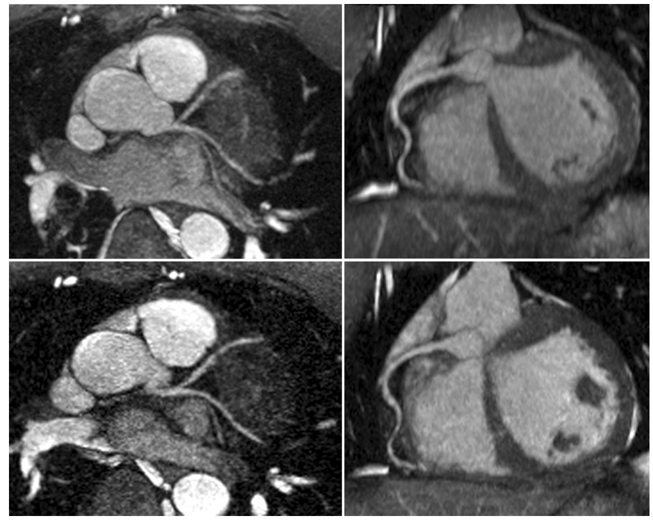

Figure 2. LAD and RCA images acquired from a 40 years old volunteer using whole-heart (top row) and volume-targeted (bottom row) methods. Note the improved visual sharpness of left and right coronary arteries for this subject using volume-targeted imaging.

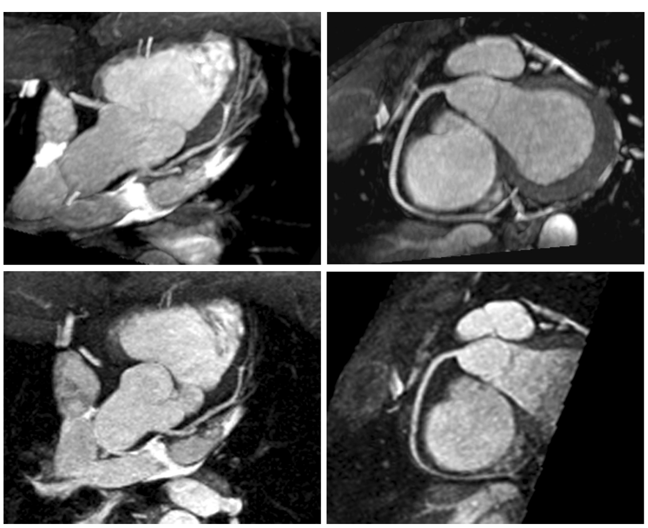

Figure 1. LAD and RCA images acquired from a 27 years old volunteer using whole-heart (top row) and volume-targeted (bottom row) methods. Coronary arteries were well depicted using both methods.

DISCUSSION

In this study, coronary artery images were acquired from healthy subjects using a magnetization-prepared, segmented SSFP sequence. Both the whole-heart and volume-targeted scans were performed using similar imaging parameters for direct comparison. The RCA and LAD coronary arteries were visualized using both imaging protocols. Statistical results showed no difference in the SNR, CNR, and vessel diameter using these two imaging methods.

The SNR using whole-heart scan (22.9 ± 8.0) were only 21.8% and 10.6% higher than that of the RCA-targeted (18.8 ± 5.9) and the LAD-targeted (20.7 ± 7.1) scans, respectively. Such increases were not statistically significant and were less than the theoretical increment (65.8%), which was proportional to the square root of the increase of the slab coverage. A possible reason for this could be, with increased coverage in the whole-heart scan, spins of the blood could have encountered several excitation RF segments and the magnetization could have been partially saturated. While for the volume-targeted scan, fresh blood spins move into the thin imaging slab in each heartbeat. Unsaturated magnetization of the blood could potentially

Table 1. Summary of the imaging time, depicted coronary artery length, vessel diameter, sharpness, SNR, and CNR from ten healthy volunteers

Subject	Imaging time (min)			Depicted vessel length (cm)				Vessel diameter (mm)				Vessel sharpness				SNR/CNR		
				RCA		LAD		RCA		LAD		RCA		LAD				
number	WH	RCA-T	LAD-T	WH	RCA-T	WH	LAD-T	WH	RCA-T	WH	LAD-T	WH	RCA-T	WH	LAD-T	WH	RCA-T	LAD-T
1	12.0	2.5	4.0	14.9	13.6	10.5	7.2	3.3	2.7	1.9	2.7	0.76	0.75	1.12	1.13	30.5/15.9	17.4/12.2	18.2/14.4
2	11.3	5.0	N/A	17.7	14.8	10.6	N/A	2.4	3.1	2.4	N/A	0.67	0.65	0.70	N/A	13.4/5.9	18.3/10.4	N/A
3	15.0	5.4	3.2	19.8	11.1	11.4	9.8	3.3	4.3	3.3	2.2	0.42	0.62	0.52	0.76	19.4/7.9	18.7/10.8	20.1/5.2
4	8.3	3.5	2.5	9.2	7.9	9.5	8.0	3.4	1.9	2.9	3.2	0.48	1.07	0.69	0.62	17.3/6.6	17.2/9.4	17.9/9.2
5	20.5	3.0	3.1	17.8	14.5	10.4	9.7	2.6	3.5	3.2	2.7	0.34	0.57	0.65	0.65	22.2/11.0	19.0/10.6	16.4/9.2
6	10.3	2.1	2.2	11.5	10.6	10.6	5.8	3.1	2.8	2.8	1.9	0.80	1.06	0.84	1.07	22.8/10.9	17.2/14.1	22.1/14.8
7	7.8	2.0	2.1	12.4	10.4	8.3	9.3	3.4	2.2	2.3	2.8	0.70	1.20	0.78	0.88	41.8/22.3	17.4/13.0	19.2/11.6
8	8.7	4.8	5.8	9.2	8.5	14.3	11.8	2.4	2.2	1.9	2.6	0.68	0.75	0.83	1.15	20.8/9.2	35.0/27.7	39.1/26.7
9	16.4	3.8	4.1	10.6	7.9	9.5	9.1	1.6	2.1	2.6	2.1	0.80	0.95	0.86	0.94	18.7/8.4	13.2/8.6	16.3/8.8
10	12.0	5.7	5.0	10.4	10.4	10.2	7.2	2.8	1.6	2.1	1.6	0.88	0.81	0.81	0.87	22.0/11.0	14.9/9.6	17.4/14.1

WH = whole-heart measurement; RCA-T = RCA-targeted measurement; LAD-T = LAD-targeted measurement. Results for the LAD-targeted imaging is not available for subject 2 because the subject decided to quit the study during the imaging session.

compensate some of the signal decrease due to smaller spatial coverage.

An important advantage of performing whole-heart coronary MRA is the larger slab coverage as compared to the conventional volume-targeted method. In addition, the overall imaging time can be reduced. In this study, although it takes 12.2 ± 4.0 minutes for one whole-heart scan, all three major coronary arteries are depicted in one such measurement. The requirement of precisely planned imaging orientation for each single coronary artery in conventional volume-targeted method is removed. The procedure of scanning planning is less demanding, which only requires a quick scout of positions of the heart and the diaphragm. As a result, the overall imaging time for performing whole-heart coronary MRA should be less or at least comparable to that using the volume-targeted method. Another advantage of performing whole-heart scan is the flexibility of post-processing the acquired images. The 3D data set can be reformatted to view each individual vessel using conventional 2D projection methods such as maximum-intensity projection (MIP), multi-planar reconstruction (MPR), or using volume rendering to provide a global view of the heart as well as the coronary arteries. Exemplary volume rendering images from the same subject shown in Fig. 1 are illustrated in Fig. 3.

The length of depicted coronary artery in volume-targeted scan depends on the selection of imaging orientation, while this is no longer a limiting factor for whole-heart scans. In this study, whole-heart coronary MRA significantly increases the depicted length of both the RCA and LAD. However, this is achieved at the cost of decreased vessel sharpness. With increased single measurement time in whole-heart scans, dynamic drift of the diaphragm position decreases the acceptance rate of respiratory gating. Furthermore, even with the subject-specific acquisition window, alterations of heart rate in an elongated imaging time may lead to data acquisition outside of the optimal diastolic quiescent period for some heartbeats. Dynamic drift and alternation of heart rate lead to volume averaging and motion blurring of the coronary vessels. Besides that, anisotropic imaging resolution might compromise the vessel sharpness especially for vessels aligned with the through-plane direction (14). All of these can lead to decreased sharpness of coronary arteries for the whole-heart scan. A recent study has shown that coronary vessel sharpness and image quality can be improved by combing imaging with a real-time heart rate variation correction algorithm (15) using volume-targeted imaging method. Such correction algorithm can be combined with the whole-heart imaging technique to improve the sharpness and quality of the depicted coronary arteries.

Further improvement of the spatial resolution will be advantageous in future studies. Parallel imaging techniques can be employed for future whole-heart studies to increase the spatial

Table 2. Comparison of measured results using whole-heart and volume-targeted methods

Imaging method	Whole-heart	RCA-targeted	LAD-targeted	
SNR	22.9 ± 8.0	18.8 ± 5.9	20.7 ± 7.1	
CNR	10.9 ± 4.9	12.6 ± 5.6	12.7 ± 6.1	
Imaging time (min)	12.2 ± 4.0	$3.8 \pm 1.4^{*}$	$3.6 \pm 1.3^{*}$	
Coronary artery	RCA		LAD	
	Whole-heart	RCA-targeted	Whole-heart	LAD-targeted
Depicted length (cm)	13.4 ± 3.9	$11.0 \pm 2.6^{*}$	10.5 ± 1.6	$8.7 \pm 1.8^{*}$
Vessel diameter (mm)	2.8 ± 0.6	2.6 ± 0.8	2.5 ± 0.5	2.4 ± 0.5
Vessel Sharpness	0.65 ± 0.18	$0.84 \pm 0.22^{*}$	0.78 ± 0.16	$0.90 \pm 0.20^{*}$

*p-value < 0.05.

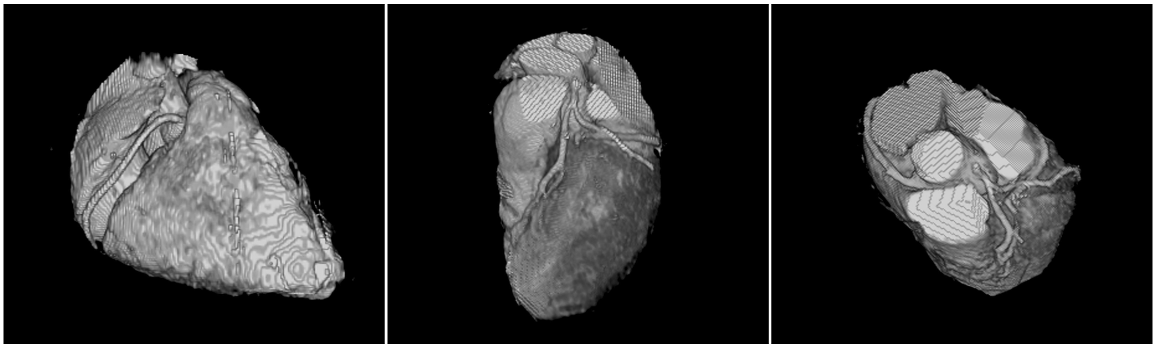

Figure 3. Reformatted volume-rendering images of the heart from one whole-heart scan. All major coronary arteries including RCA, LAD, and LCX are well depicted in this subject.

resolution and/or decrease the imaging time (16, 17). In addition, acquiring images with isotropic resolution in all directions will be ideal for reformatting of the 3D data set (14, 18).

In consideration of the advantages and disadvantages of these two imaging methods, a combination of the whole-heart and volume-targeted scans could have potential applications in coronary MRA. A relatively low-resolution (1 mm–2 mm) whole-heart scan with parallel imaging techniques can firstly be run as a scout scan. Then, the courses of all major coronary arteries could be defined from the acquired image series. Furthermore, potential diseased coronary vessel could be identified from the acquired images. Volume-targeted scan will then be prescribed with better resolution and sharpness to define the severity of stenosis.

In conclusion, this paper presents a comparison of coronary MRA on healthy volunteers using the whole-heart and volume-targeted methods. The depicted length of coronary arteries was longer using the whole-heart scan, while the vessel is sharper using the volume-targeted method. Combination of the whole-heart and volume-targeted methods could be potentially useful in clinical applications of coronary MRA. In addition, combining parallel imaging technique and motion correction techniques will be helpful to improve the image quality in future studies.

REFERENCES

1. Botnar RM, Stuber M, Danias PG, Kissinger KV, Manning WJ. Improved coronary artery definition with T2-weighted, free-breathing, three-dimensional coronary MRA. Circulation 1999;99: 3139–48.
2. Kim WY, Danias PG, Stuber M, Flamm SD, Plein S, Nagel E, Langerak SE, Weber OM, Pedersen EM, Schmidt M, Botnar RM, Manning WJ. Coronary magnetic resonance angiography for the detection of coronary stenoses. N Engl J Med 2001;345: 1863–69.
3. Manning WJ, Li W, Boyle NG, Edelman RR. Fat-suppressed breath-hold magnetic resonance coronary angiography. Circulation 1993;87:94–104.
4. Weber OM, Pujadas S, Martin AJ, Higgins CB. Free-breathing, three-dimensional coronary artery magnetic resonance angiography: comparison of sequences. J Magn Reson Imaging 2004;20:395–402.
5. Weber OM, Martin AJ, Higgins CB. Whole-heart steady-state free precession coronary artery magnetic resonance angiography. Magn Reson Med 2003;50:1223–8.
6. Hofman MB, Wickline SA, Lorenz CH. Quantification of in-plane motion of the coronary arteries during the cardiac cycle: implications for acquisition window duration for MR flow quantification. J Magn Reson Imaging 1998;8:568–76.
7. Wang Y, Ehman RL. Retrospective adaptive motion correction for navigator-gated 3D coronary MR angiography. J Magn Reson Imaging 2000;11:208–14.
8. Spuentrup E, Stuber M, Botnar RM, Kissinger KV, Manning WJ. Real-time motion correction in navigator-gated free-breathing double-oblique submillimeter 3D right coronary artery magnetic resonance angiography. Invest Radiol 2002;37:632–6.
9. Shea SM, Deshpande VS, Chung YC, Li D. Three-dimensional true-FISP imaging of the coronary arteries: improved contrast with T2-preparation. J Magn Reson Imaging 2002;15:597–602.
10. Deshpande VS, Chung YC, Zhang Q, Shea SM, Li D. Reduction of transient signal oscillations in true-FISP using a linear flip angle series magnetization preparation. Magn Reson Med 2003;49: 151–7.
11. Stuber M, Botnar RM, Danias PG, Sodickson DK, Kissinger KV, Van Cauteren M, De Becker J, Manning WJ. Double-oblique free-breathing high resolution three-dimensional coronary magnetic resonance angiography. J Am Coll Cardiol 1999;34:524–31.
12. Stuber M, Botnar RM, Fischer SE, Lamerichs R, Smink J, Harvey P, Manning WJ. Preliminary report on in vivo coronary MRA at 3 Tesla in humans. Magn Reson Med 2002;48:425–9.
13. Li D, Carr JC, Shea SM, Zheng J, Deshpande VS, Wielopolski PA, Finn JP. Coronary arteries: Magnetization-prepared contrast-enhanced three-dimensional volume-targeted breath-hold MR angiography. Radiology 2001;219:270–7.
14. Botnar RM, Stuber M, Kissinger KV, Manning WJ. Free-breathing 3D coronary MRA: The impact of "isotropic" image resolution. J Magn Reson Imaging 2000;11:389–93.
15. Leiner T, Katsimaglis G, Yeh EN, et al. Correction for heart rate variability improves coronary magnetic resonance angiography. J Magn Reson Imaging 2005;22:577–82.
16. Griswold MA, Jakob PM, Heidemann RM, Nittka M, Jellus V, Wang J, Kiefer B, Haase A. Generalized autocalibrating partially parallel acquisitions (GRAPPA). Magn Reson Med 2002;47:1202–10.
17. Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. SENSE: sensitivity encoding for fast MRI. Magn Reson Med 1999;42:952–62.
18. Stehning C, Bornert P, Nehrke K, Eggers H, Dossel O. Fast isotropic volumetric coronary MR angiography using free-breathing 3D radial balanced FFE acquisition. Magn Reson Med 2004;52:197–203.