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Improved Image Quality of Coronary CT Angiography Using Automatic Motion Correction

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Background: Motion artifacts that degrade image quality of coronary CT angiography (CCTA) in patients with high heart rates may be reduced with specific automatic motion correction algorithms (AMC).
Objectives: We compared coronary-artery delineation between AMC and conventional CCTA reconstruction (CR).
Patients and Methods: CCTA images (clinical single-source-64-slice-CT system) of 17 consecutive patients with heart rates exceeding 55 bpm were reconstructed with both CR and AMC during the individually best-suited phase of the cardiac cycle. Two independent readers who were blinded to the reconstruction algorithm scored image quality of each coronary artery segment (AHA 15-segment-model; 1: non-diagnostic - 4: excellent). In case of disagreement a third blinded reader assigned a final score. Two-tailed statistical tests (Wilcoxon-matched-pairs, Pearson-correlation) were significant at $P < 0.05$.
Results: Mean heart rate during CCTA was 61 ± 8 bpm. CCTA quality improved significantly in the RCA (good-or-excellent in 11/17 AMC vs. 5/17 CR, $P = 0.018$) and LAD (15/17 vs. 7/17, $P = 0.031$). Non-diagnostic CCTA in the RCA, LM, LAD, and LCX reduced from 16/68 (CR, 24%) to 7/68 (AMC, 10%). Significant motion correction was observed at low (≤ 60 bpm; $P = 0.008$), intermediate (61-70 bpm; $P < 0.001$), and high heart rates (> 70 bpm; $P = 0.021$). Inter-reader agreement was good. (inter-class-correlation, 0.762).
Conclusions: CCTA image quality improves significantly with AMC in patients with high heart rates and reduces the proportion of non-diagnostic examinations.

Keywords: CCTA; Motion Correction; Image Quality

1. Background

With continuous technical development of computed tomography (CT), coronary CT angiography (CCTA) has emerged as a useful diagnostic tool in clinical practice. The main challenge in imaging the coronary arteries remains their fast motion during the cardiac cycle, which reaches up to 70 mm-per-second in the right coronary artery (1). Although the temporal resolution of modern CT systems with approximately 66-150 ms per volume-data-set is still significantly lower when compared to invasive coronary angiography, diagnostic image quality of CCTA can be achieved in a majority of patients when image data are reconstructed at the right time point of the cardiac cycle. Consequently, a very high diagnostic accuracy has been demonstrated for CCTA in several studies (2, 3). CCTA, however, often suffers from motion artefacts, especially in patients with higher heart rates. Therefore, heart rate control is essential for CCTA (4). However, despite treatment with beta-blockers, a low heart rate is not achieved in all patients. In patients with persistently high heart rates, CCTA reconstruction algorithms that reduce motion artifacts are desirable. Specific automated motion correction algorithms (AMC) have been developed to reduce motion artifacts of the coronary arteries. Recently, a vendor-specific AMC (Snapshot Freeze, GE Healthcare, WI, USA) has been shown to improve image quality in patients with high heart rates in both prospectively ECG-triggered sequential scan mode (5) and helical scan mode (6).

2. Objectives

We compared coronary-artery delineation between AMC and conventional CCTA reconstruction (CR) in a cohort of consecutive patients comprising both sequential and helical CCTA examinations.

3. Patients and Methods

In a retrospective study that was approved by the institutional review board, we analyzed image data of 17 consecutive patients who were referred for CCTA to rule out coronary artery disease between July and October, 2013. Patients provided written informed consent to the CT examination and to the secondary use of CCTA data for scientific purposes.

Patients had heart rates exceeding 55 bpm during breath holding in inspiration and were eligible for CCTA scan modes allowing for AMC. Patients with known allergy against the contrast agent, renal insufficiency, or hyperthyroidism were excluded. All patients were examined on a single-source 64-slice-CT system (GE Healthcare, Optima CT660).

3.1. Scan Protocol

Patients with a heart rate of 55 – 65 bpm were examined with a prospectively ECG-triggered sequential scan mode and additional 80-ms-padding to obtain sufficient image data for triple-phase image reconstruction which is required for the AMC. In patients with heart rates exceeding 65 bpm, a retrospectively ECG-gated helical CT with ECG-dependent tube current modulation and maximum tube current between 45% and 75% of the RR-interval was performed, which provides sufficient image data for motion correction.

Prior to the examination an ante-cubital intravenous catheter was placed. Patients with a heart rate exceeding 60 bpm were administered up to 20 mg metoprolol-tartrate intravenously. Patients with a systolic blood pressure exceeding 100 mmHg were administered nitrates sublingually. To allow for an ECG-synchronized examination, ECG-electrodes were placed on the patients' chest. All CT examinations were performed on a commercially available single-source-64-slice-CT system (GE Healthcare, Optima CT660, Milwaukee, WI, USA). After acquiring a scout image, CT angiography was planned to cover the entire heart. Initiation of CCTA was timed using bolus tracking. An amount of 80 mL of iodinated contrast medium (Imeron 350, Bracco Imaging Group, Milan, Italy) was injected at a rate of 6 mL/s, followed by a saline chaser of 50 mL, with manual scan initiation at the onset of contrast enhancement in the ascending aorta. CT acquisition parameters included: slice collimation, 64×0.625 mm; gantry rotation time, 350 ms; tube voltage adapted to individual chest physiognomy; automated tube current modulation enabled at noise index of 22.1. Image acquisition was performed in cranio-caudal scan direction.

3.2. Image Reconstruction

All examinations were reconstructed conventionally (CR), during the individually best-suited phase of the cardiac cycle, and correspondingly using the AMC "SnapShot Freeze®". The AMC requires image data gain at the best-suited time point of the cardiac cycle, and at 78 ms prior to and after that time point. Following automatic coronary artery tree segmentation, the SAMC automatically analyzes motion direction and velocity of the coronary arteries in the multi-phase data set. Using motion information, the AMC calculates a motion-corrected data set for the underlying cardiac phase. The technical principles of the AMC have been published previously (7). All images were reconstructed with 0.625 mm slice thickness, a standard reconstruction kernel, and a contribution of two-dimensional iterative image reconstruction (ASIR) to filtered-back-projection of 50%.

3.3. Evaluation of Image Quality

Two independent radiologists, who were unaware of the different CCTA reconstruction algorithms, evaluated delineation of different coronary artery segments in all datasets, according to the American Heart Association (AHA) modified 15-segment model (8). A third experienced reader summarized results and assigned a final image quality score. The datasets consisted in axial slices and multiplanar reformations which were anonymized and analyzed in random order. Image quality of every coronary artery segment with at least 1.0 mm diameter were scored according to a 4-point grading-scale (1: non-diagnostic image quality; 2: significantly reduced image quality due to major artifacts, but still diagnostic; 3: good image quality with minor artifacts; 4: excellent image quality without artifacts; Figure 1).

Furthermore, the presence of definite or probable significant coronary artery stenosis and the presence of coronary atherosclerotic plaques were recorded.

3.4. Radiation Dose

CT dose index (CTDIvol) and dose–length product (DLP) were obtained from the CT scanning protocol of each CCTA study. For estimation of the effective dose, the product of the DLP and an organ weighting factor (k = 0.017 mSv × (mGy ×cm)–1) was calculated, as proposed by the European Working Group for Guidelines on Quality Criteria in CT (9).

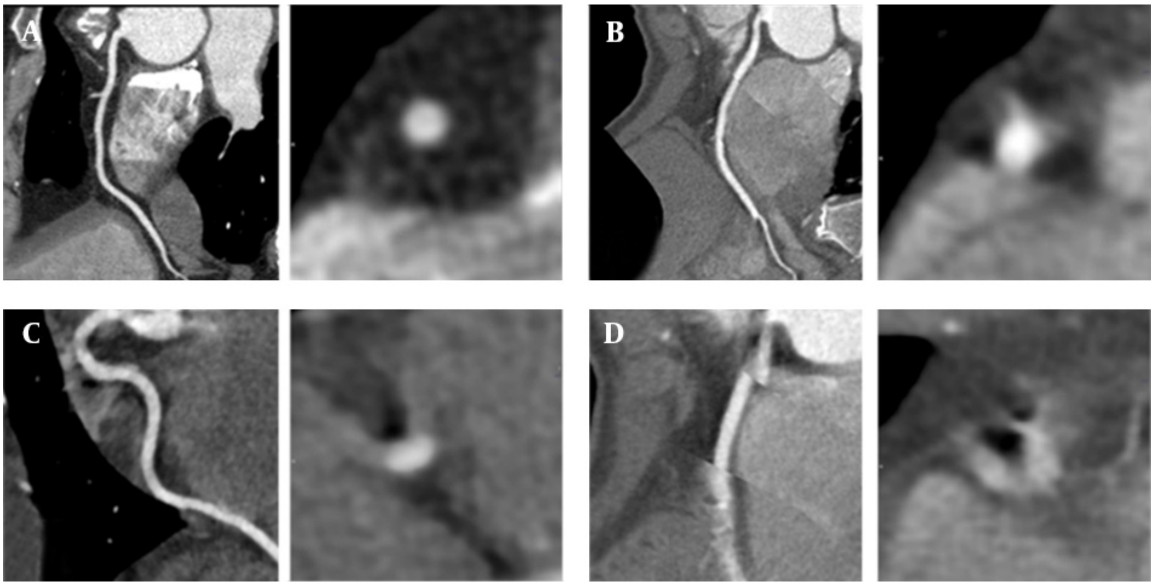
3.5. Statistical Analysis

Variables were compared between CR and AMC data sets for each patient. Continuous normally distributed variables were expressed as mean ± standard deviation and were compared using the Wilcoxon's rank sum test. The image quality scores between both groups were compared using the Wilcoxon's rank sum test. Categorical variables were expressed as frequencies and percentages and compared using the chi-square-test. To evaluate inter-reader-variability between readers 1 and 2, intra-class correlation ICC) was performed. Correlation between heart rate and image quality was conducted using Pearson's correlation coefficient. A p value of < 0.05 was considered to be statistically significant. All statistical analyses were performed using SPSS software (version 20.0.0, SPSS Inc.)

4. Results

Patient and scan characteristics are displayed in Table 1. Mean effective radiation dose was 4.7 ± 2.8 mSv. Mean heart rate during the examination was 61 ± 8 bpm.

Figure 1. This figure Shows Examples for Different Grades of Image Quality



Curved MPR's (left) and axial images (right) of the right coronary artery with image quality score 4 (a), 3 (b), 2 (c) and 1 (d) are displayed.

Table 1. Patient and Scan Characteristics [a]

Variables	Frequency
Patient characteristics	
Number of patients	17
Age, y	58 ± 13
Male	7 (41)
Height, m	1.72 ± 0.11
Weight, kg	81 ± 17
Indication	
Dyspnea	1 (6)
Paroxysmal arrhythmia	5 (29)
Thoracic pain	11 (65)
Sinus rhythm	17 (100)
Heart rate, bpm	61 ± 8
Intravenous beta-blocker	14 (82)
Nitroglycerin sublingual	17 (100)
Scan characteristics	
Tube voltage	
100 kV	8 (47)
120 kV	9 (53)
Scan mode	
sequential	12 (71)
spiral	5 (29)
Tube current, mAs	453 ± 100
Dose-length-product, mGy x cm	279 ± 163
Effective radiation dose, mSv, (weighting factor) 0.017 mSv × (mGy ×cm)–1)	4.7 ± 2.8

[a] Data are presented as No. (%) or Mean ± SD.

On a per-patient basis, AMC improved image quality in 10/17 patients (59%) for reader 1, and 14/17 patients (82%) for reader 2. Among the 17 patients, 7 patients showed calcified plaques, and 5 patients showed non-calcified plaques. In 2 patients, significant coronary artery stenosis was found.

On a per-vessel basis, application of AMC was associated with a statistically significant improvement in image quality in the right coronary artery and left anterior descending artery (Table 2).

On a per-segment basis, a total of 410 coronary artery segments with diameter ≥1.0 mm were available for evaluation of image quality (on average, 12 segments per patient). Fourty-four coronary artery segments had a diameter of less than 1.0 mm, and 56 coronary artery segments were missing due to anatomical variants.

The proportion of coronary artery segments with very good or good image quality increased significantly, from 73.2% with CR to 89.9% with AMC ($P < 0.001$, Figure 2), and the rate of non-diagnostic coronary artery segments dropped from 9.9% to 6.3%. Inter-reader agreement on image quality of coronary artery segments was good, with an ICC of 0.762. Inter-reader variability decreased with AMC (ICC 0.786) when compared with CR images (ICC 0.726).

Significant improvement in image quality with AMC was observed for low heart rates (≤ 60 bpm; $P = 0.008$), intermediate heart rates (61-70 bpm; $P < 0.001$), and high heart rates (> 70 bpm; $P = 0.021$, Figure 3). We observed a significant inverse correlation between heart rate during image acquisition and image quality scores ($r = -0.426$; $P < 0.001$), which was more pronounced in CR images ($r = -0.467$; $P < 0.001$) than in AMC images ($r = -0.405$; $P < 0.001$).

Table 2. significant improvement in image quality in the right coronary artery and left anterior descending artery [a,b]

Vessel	Image Quality Score	Motion Correction (AMC) (n = 17 Patients)		P Value
		Yes	No	
RCA				0.018
	1	3 (18)	9 (53)	
	2	3 (18)	3 (18)	
	3	8 (47)	4 (24)	
	4	3 (18)	1 (6)	
LM				0.361
	1	0 (0)	1 (6)	
	2	0 (0)	0 (0)	
	3	2 (13)	4 (25)	
	4	14 (88)	11 (69)	
LAD				0.031
	1	1 (6)	3 (18)	
	2	1 (6)	7 (41)	
	3	10 (59)	5 (29)	
	4	5 (29)	2 (12)	
LCX				0.099
	1	3 (18)	3 (18)	
	2	0 (0)	6 (35)	
	3	9 (53)	6 (35)	
	4	5 (29)	2 (12)	

[a] Abbreviations: LAD, left anterior descending artery; LCX, left circumflex artery; LM, left main coronary artery; RCA, right coronary artery.
[b] Data are presented as No. (%).

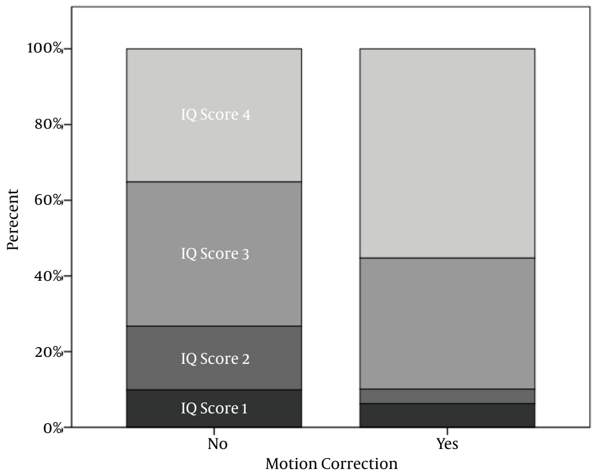


Figure 2. This Bar Diagram Displays the Rate of Different Image Quality Scores in Conventionally Reconstructed (left bar) and Motion Corrected Images (Right Bar)

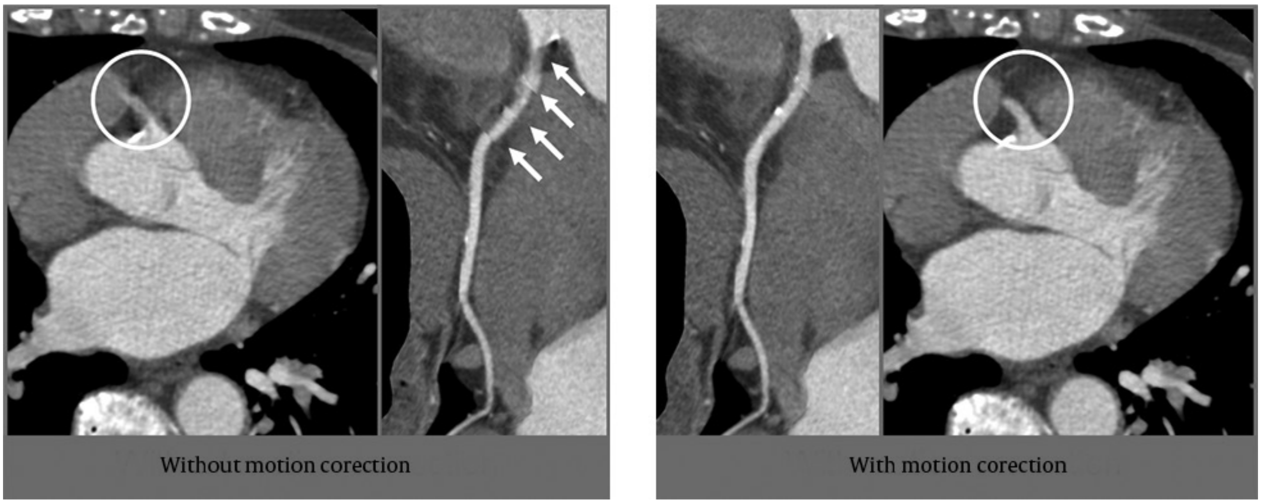
5. Discussion

This analysis demonstrates that application of an automatic motion correction algorithm (AMC) has the potential to significantly improve image quality of CCTA. In particular, the rate of non-diagnostic coronary artery segments decreased significantly.

Our results corroborate previous observations by Leipsic et al. (6) in 36 patients who were examined for planning purposes prior to transcatheter aortic valve replacement. Application of AMC improved image quality, increased the rate of diagnostic coronary artery segments, and improved diagnostic accuracy when compared to invasive angiography (6). We observed the most pronounced impact of motion correction on image quality in the right coronary artery, which also was most frequently affected by reduced image quality due to motion artifacts. This finding is concordant with a study by Fuchs et al. that also showed the highest impact on image quality for the right coronary artery in patients who were all examined using a prospectively ECG-triggered sequential scan mode (5).

In our patient cohort, with heart rates exceeding 55 bpm, the rate of a non-diagnostic right coronary artery scans was 53% in CR images. However, with AMC, the right coronary artery showed diagnostic image quality in 82% percent of patients. The effect of automatic motion correction was also significant, if less pronounced, for the left anterior descending artery. However, while AMC improved image quality in the left main artery and the left circumflex artery, the respective differences did not reach statistical significance.

Figure 3. Sixty-Six-Year-Old Female Patient With a High Mean Heart rate of 73 bpm During Image Acquisition With Retrospectively ECG-Gated Helical CCTA



Conventionally reconstructed images (left side) show significant motion artifact in the proximal right coronary artery that hamper assessment of significant coronary artery stenosis. With automatic motion correction (right side) significant stenosis in the right coronary artery was excluded.

The AMC we applied requires image data sampling acquisition at one particular time point within the cardiac cycle that corresponds to the target cardiac phase at prospectively ECG-triggered CCTA, and at adjacent time points 78 ms prior to and after that time point, which is referred to as “padding”. Based on this tri-phasic data set, the AMC first performs automatic coronary artery tree segmentation and subsequently analyzes direction and velocity of motion of each coronary artery. The SAMC then calculates a motion-corrected data set at the target cardiac phase. However, the additional padding, 78 ms prior to and after the target cardiac phase, increased radiation exposure by up to 60 percent in our patients.

In patients examined with a retrospectively ECG-gated scan technique, the required image data adjacent to the target cardiac phase are available automatically, such that there is no increase in radiation exposure. In contrast to padding in conjunction with an AMC, as applied in our study, it has been shown by Labounty et al. (10) in a multicenter trial that padding alone, with the purpose of obtaining additional reconstruction time points in the cardiac cycle, but without application of AMC, does not improve CCTA. Therefore, it appears that additional radiation exposure as required for padding is justified only in conjunction with a reconstruction algorithm that applies the additional image data to improve image quality, such as in the AMC we applied here.

5.1. Limitations

The results of this study should be interpreted in view of the retrospective study design, the relatively small number of patients, and the resulting limitations. Depsite these limitations, we observed significant improvement in image quality when using the automatic motion correction, particularly in the left anterior descending artery and the right coronary artery, which may underline the high potential of the AMC applied here.

Patients included in our study did not undergo invasive coronary angiography, such that we did not evaluate if the improvement of image quality also increased the diagnostic accuracy of CCTA. Therefore, it may only be assumed that diagnostic accuracy would increase as a consequence of improved image quality at CCTA.

Furthermore, the AMC we applied is vendor-specific. Therefore, it has to remain unclear if the results of this study would transfer to CT systems offered by other vendors.

Application of an automated motion correction algorithm to CCTA significantly decreases motion artefacts and improves image quality, particularly in the left anterior descending artery and the right coronary artery, and shows potential to decrease the rate of non-diagnostic CCTA examinations.

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