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COMPUTED TOMOGRAPHY

Second-generation motion correction algorithm improves diagnostic accuracy of single-beat coronary CT angiography in patients with increased heart rate

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Abstract

Objective To assess the effect of a second-generation motion correction algorithm on the diagnostic accuracy of coronary computed tomography angiography (CCTA) using a 256-detector row CT in patients with increased heart rates.

Methods Eighty-one consecutive symptomatic cardiac patients with increased heart rates (≥ 75 beats per min) were enrolled. All patients underwent CCTA and invasive coronary angiography (ICA). CCTA was performed with a 256-detector row CT using prospectively ECG-triggered single-beat protocol. Images were reconstructed using standard (STD) algorithm, first-generation intra-cycle motion correction (MC1) algorithm, and second-generation intra-cycle motion correction (MC2) algorithm. The image quality of coronary artery segments was assessed by two experienced radiologists using a 4-point scale (1: non-diagnostic and 4: excellent), according to the 18-segment model. Diagnostic performance for segments with significant lumen stenosis (≥ 50%) was compared between STD, MC1, and MC2 by using ICA as the reference standard.

Results The mean effective dose of CCTA was 1.0 mSv. On per-segment level, the overall image quality score and interpretability were improved to 3.56 ± 0.63 and 99.2% due to the use of MC2, as compared to 2.81 ± 0.85 and 92.5% with STD and 3.21 ± 0.79 and 97.2% with MC1. On per-segment level, compared to STD and MC1, MC2 improved the sensitivity (92.2% vs. 79.2%, 80.7%), specificity (97.8% vs. 82.1%, 90.8%), positive predictive value (89.9% vs. 48.4%, 65.1%), negative predictive value (98.3% vs. 94.9%, 95.7%), and diagnostic accuracy (96.8% vs. 81.5%, 89.0%).

Conclusion A second-generation intra-cycle motion correction algorithm for single-beat CCTA significantly improves image quality and diagnostic accuracy in patients with increased heart rate.

Key Points

- *A second-generation motion correction (MC2) algorithm can further improve the image quality of all coronary arteries than a first-generation motion correction (MC1).*
- *MC2 algorithm can significantly reduce the number of false positive segments compared to standard and MC1 algorithm.*

Keywords Coronary vessels · Tomography, X-ray computed · Heart rate · Motion · Coronary angiography

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Abbreviations

AUC	Area under curve
bpm	Beats per minute
CAD	Coronary artery disease
CCTA	Coronary computed tomography angiography
HRV	Heart rate variability
ICA	Invasive coronary angiography
LAD	Left anterior descending artery
LCX	Left circumflex artery
MC1	First-generation motion correction
MC2	Second-generation motion correction
NPV	Negative predictive value

PPV Positive predictive value
RCA Right coronary artery
STD Standard

Introduction

Motion artifacts represent a technical challenge in coronary computed tomography angiography (CCTA) and can influence the accurate assessment of coronary arteries, especially in patients with increased heart rates [1, 2]. Guidelines recommend that heart rates should be lowered to less than 60 beats per minute (bpm) by orally or intravenously administered medication [3]. However, a survey has shown that 50% of 141 centers allow heart rate > 70 bpm for CCTA in the USA [4]. Another survey has reported that heart rate threshold was set to 70 bpm even β-blockers were routinely used in 86% of 45 centers in Germany [5]. Further, 5–11% of patients have contraindications or intolerance to medications that are used to lower the heart rate [2, 6].

Technical developments in CT systems have improved the temporal resolution, including increased gantry rotation speeds, dual-source CT, multi-segment reconstruction, and software solutions, for correcting motion artifacts [7]. Wide-detector CT enables image acquisition within one heartbeat, shortens the scan time [8], and reduces the negative impact of elevated heart rate variability on image quality [9, 10]. The latest volumetric, one heartbeat, single-source CT scanner allows the acquisition of diagnostic images in patients with elevated heart rates using a first-generation intra-cycle motion correction (MC1) algorithm [11–16]. However, in a recent study by Liang et al [11], it has been reported that, even with MC1, there were still non-diagnostic images and false-positive cases caused by motion artifacts in patients with elevated heart rates.

A second-generation intra-cycle motion correction (MC2) algorithm has been introduced recently as a prototype to overcome or improve the shortcomings of MC1 algorithm; however, its clinical value in diagnosing patients with elevated heart rates is yet to be investigated. Thus, the purpose of this study was to determine the effect of MC2 on the assessment of coronary arteries and diagnostic performance of CCTA in patients with increased heart rates.

Materials and methods

Study population

This research received the approval from the local institutional review board. All patients provided informed written consent before the commencement of the study. From April 2016 to February 2017, 116 consecutive symptomatic patients with known or suspected coronary artery disease (CAD) were prospectively enrolled. All patients underwent CCTA and invasive coronary angiography (ICA). We included patients in regularity of cardiac rhythm with heart rates higher than or equal to 75 bpm during the CT scan. Exclusion criteria included past history of hypersensitivity to the iodinated contrast agent, nephropathy (estimated glomerular filtration rate ≤ 60 mL/min), heart rate variability more than 20 bpm, any type of arrhythmias, pregnancy, and previous stent and/or bypass graft surgery. Overall, thirty-five patients were excluded according to these criteria; of them, 15 were excluded due to irregular rhythms or heart rate variability more than 20 bpm; 16 were excluded because of prior stenting; and four were excluded due to previous history of coronary bypass grafting surgery. Finally, 81 patients who had both CCTA and ICA examinations within 4 weeks were included in the study. Figure 1 shows the flowchart of patient recruitment.

CCTA scanning protocols

All examinations were performed on a 256-row detector CT scanner (Revolution CT, GE Healthcare) with prospectively electrocardiography triggering in a single heartbeat. Scanning parameters were as follows: z-coverage was 12 cm, 14 cm, or 16 cm with a matrix size of 512 × 512 pixels depending on the patient's heart size between the level of carina and diaphragm; voxel size was 0.625 mm; gantry rotation time was 280 milliseconds; tube voltage was 100 kV or 120 kV selected by kV assist; tube current was Smart-mA technique. A cardiac bowtie was used to target the heart with a scan field view of 360 mm to minimize the radiation dose. The display field-of-view (DFOV) for the image reconstruction was 250 mm with an image slice thickness and interval of 0.625 mm. Data acquisition was triggered using a bolus-tracking technique, which started 9.0 s after the attenuation value in the descending aorta became higher than the triggering threshold of 110 Hounsfield units. When the heart rate was lower than 80 bpm but higher than 75 bpm, data acquisition covering 40–55% of the R-R interval was performed. When the heart rate was higher than 80 bpm, 30–60% of the R-R interval was acquired. Next, 50–60 mL of the contrast agent, iopromide (370 mg iodine/mL, Ultravist, Bayer Schering Pharma), was injected through an antecubital vein at a flow rate of 4.0–5.0 mL/s using an 18-gauge catheter, followed by 30 to 35 mL of saline solution. The dose and flow rate of the contrast agent were determined according to the body mass index and vein condition.

CCTA image reconstruction and analysis

All images were reconstructed using the standard (STD) (without motion correction) algorithm with 50% of a new adaptive statistical iterative reconstruction-v (ASIR-V, GE

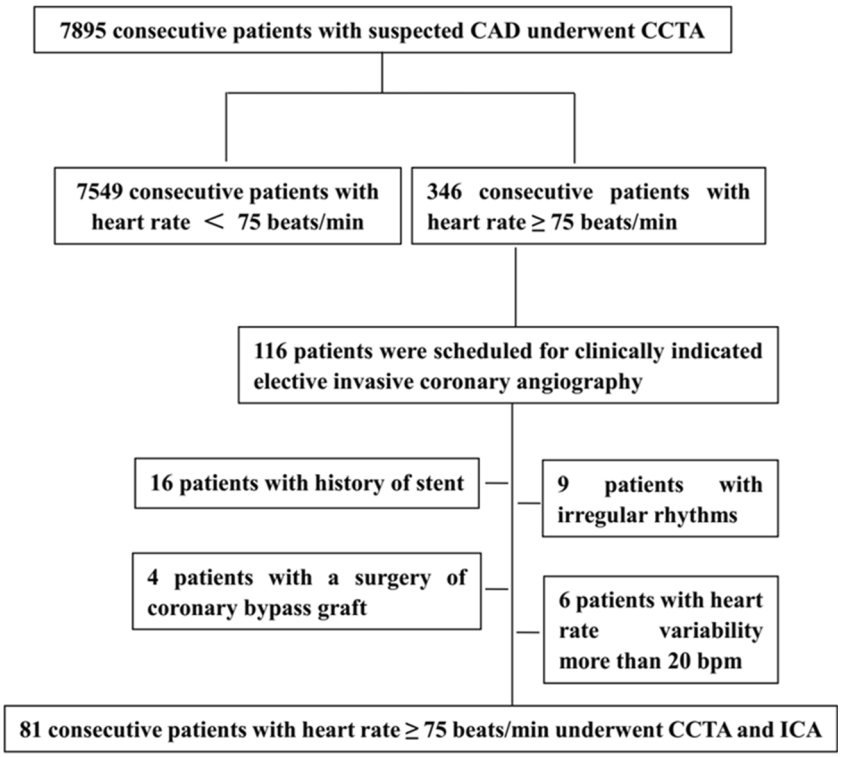

Fig. 1 Flow chart presents recruitment of eligible patients in this study. CAD, coronary artery disease; CCTA, coronary computed tomography angiography; ICA, invasive coronary angiography

Healthcare) for reducing the image noise. The cardiac phase with the least motion artifacts was selected from the systolic phases by an experienced radiologist (with more than 10 years of experience in cardiac CT). Images from the optimal target phase were additionally reconstructed with MC1 and MC2 algorithms. MC1 algorithm was applied on a workstation (AW 4.6 Advantage Workstation, GE Healthcare). The images from MC2 algorithm were reconstructed on an off-site computer. Both MC1 and MC2 algorithms used the data from adjacent cardiac phases (60 milliseconds before and after the target phase) to characterize and correct the motion. The MC1 algorithm has been previously described [14, 17]. The MC2 algorithm, which is a fully automated technique based on knowledge and feedback obtained from MC1, seeks each region of all image volumes for a local path that is consistent with the subset of measured data. Once the vessel's motion path is identified, the data are discretized into a series of datasets based on when the corresponding projection rays were measured. Each volume dataset in the series undergoes the process of spatial deformation by the motion field. This allows the motion state to be mapped from the respective time to the central reference time, which is determined by the prescribed cardiac phase [15].

Two independent cardiovascular radiologists (with 9 and 10 years of experience in CCTA) who were blinded to the reconstruction algorithms assessed the image quality of coronary segments. STD, MC1, and MC2 reconstructions were analyzed in a random order with an interval of at least 3 weeks to minimize any reader bias. In addition, curved multi-planar reformat reconstructions and axial datasets were assessed to detect lesions by each reader. Coronary artery segments with a lumen longer than 15 mm and diameter of 1.5 mm or more were evaluated according to the 18-segment model, which is modified by the Society of Cardiovascular Computed Tomography [3]. Accordingly, a 4-point grading scale system was used to evaluate the image quality [16, 18]. Score 1 denotes non-diagnostic image quality (severe artifacts with inadequate

Table 1 Study characteristics of the participants

	($n = 81$)
Patient's characteristics	
Mean age (years)	58.7 ± 9.8 (31~76)
Sex	
Male	47 (58.0%)
Female	34 (42.0%)
Body mass index (kg/m^2)	24.8 ± 3.0 (17.4~31.0)
Heart rate (beats per min)	83.8 ± 8.9 (75~134)
HR variability (beats per min)	10.2 ± 4.8 (1~17)
Hypertension (≥ 140/90 mmHg)	56 (69.1%)
Hypercholesterolemia (> 200 mg/dL)	11 (13.6%)
Current smoking	23 (28.4%)
Drinking (≥ 50 mL/time, frequently)	15 (18.5%)
Diabetes mellitus (II)	23 (28.4%)
Family history of CAD	16 (19.8%)

Values are represented as mean ± SD (range) or n (%)

Table 2 CCTA scanning parameters and radiation dose

	($n = 81$)
Tube voltage (kV)	
100	78 (96.3%)
120	3 (3.7%)
Tube current (mA)	446.7 ± 56.7 (236~629)
Coverage (mm)	
120	3 (3.7%)
140	70 (86.4%)
160	8 (9.9%)
CTDIvol (mGy)	5.0 ± 1.4 (2.5~10.6)
DLP (mGy cm)	69.9 ± 19.6 (35.2~148.6)
ED (mSv)	1.0 ± 0.3 (0.4~2.1)

Values are represented as mean ± SD (range) or n (%)

CTDI computed tomography dose index, *DLP* dose length product, *ED* Effective dose

delineation between the lumen and the surrounding tissue); 2 denotes adequate image quality (noticeably blurred vessel, but acceptable for diagnosis); 3 denotes good image quality (blurring of vessel margin and minor artifacts, fully evaluable); and 4 denotes excellent image quality (with the absence of artifacts). When there was difference in scoring, a consensus was reached after negotiation between the two radiologists. Coronary segment was considered interpretable when it had image quality score of 2 to 4 and non-interpretable when the score was 1. The interpretability was calculated as the percentage of interpretable segments over total number of evaluable segments. The degree of significant coronary artery stenosis was defined by a diameter reduction of more than 50%, and it was evaluated independently by the same radiologists. This analysis was done on a per-segment, per-artery, and per-patient basis. Non-diagnostic segments were treated as positive findings. In case of any disagreement on lumen stenosis between two readers, a joint reading was performed to reach consensus agreement.

Invasive coronary angiography

Conventional ICA was used as a reference technique to diagnose significant stenosis. Angiograms were analyzed by two independent interventional cardiologists (with 8

Table 3 Image quality scores of segment, artery, and interpretability among the three reconstruction algorithms

Image quality and interpretability	STD	MC1	MC2	*p* (STD v MC1)	*p* (STD v MC2)	*p* (MC1 v MC2)
Segment score						
1	7.5 (82/1096)	3.0 (33/1096)	0.8 (9/1096)	< 0.001	< 0.001	< 0.001
2	25.2 (276/1096)	14.2 (156/1096)	5.4 (59/1096)	< 0.001	< 0.001	< 0.001
3	46.5 (510/1096)	41.9 (459/1096)	30.5 (334/1096)	0.028	< 0.001	< 0.001
4	15.6 (228/1096)	40.9 (448/1096)	63.3 (694/1096)	< 0.001	< 0.001	< 0.001
Artery mean score						
RCA	2.87 ± 0.81	3.32 ± 0.73	3.68 ± 0.53	< 0.001	< 0.001	< 0.001
LM	3.57 ± 0.55	3.74 ± 0.47	3.93 ± 0.26	0.003	< 0.001	0.001
LAD	2.75 ± 0.81	3.13 ± 0.78	3.51 ± 0.66	< 0.001	< 0.001	< 0.001
LCX	2.56 ± 0.90	2.99 ± 0.88	3.36 ± 0.73	< 0.001	< 0.001	< 0.001
Interpretability on every artery						
RCA	82.7 (67/81)	96.3 (77/81)	98.8 (80/81)	0.001	< 0.001	0.250
LM	100.0 (81/81)	100 (81/81)	100 (81/81)	1.000	1.000	1.000
LAD	76.5 (62/81)	91.4 (74/81)	98.8 (80/81)	< 0.001	< 0.001	0.006
LCX	65.4 (53/81)	81.7 (67/81)	96.3 (78/81)	< 0.001	0.012	0.001
Interpretability						
Per-segment	92.5 (1014/1096)	97.2 (1063/1096)	99.2 (1087/1096)	< 0.001	< 0.001	< 0.001
Per-artery	81.2 (263/324)	92.6 (300/324)	98.5 (319/324)	< 0.001	< 0.001	< 0.001
Per-patient	56.8 (46/81)	77.8 (63/81)	95.1 (77/81)	< 0.001	< 0.001	0.002

Values are represented as mean ± SD or % (n/N)

Wilcoxon matched pairs signed-ranks test was used to test the difference in image quality and artery score

McNemar's test was used to test the difference of interpretability

STD standard, *MC1* first generation motion correction, *MC2* second-generation motion correction, *RCA* right coronary artery, *LM* left main, *LAD* left anterior descending artery, *LCX* left circumflex artery

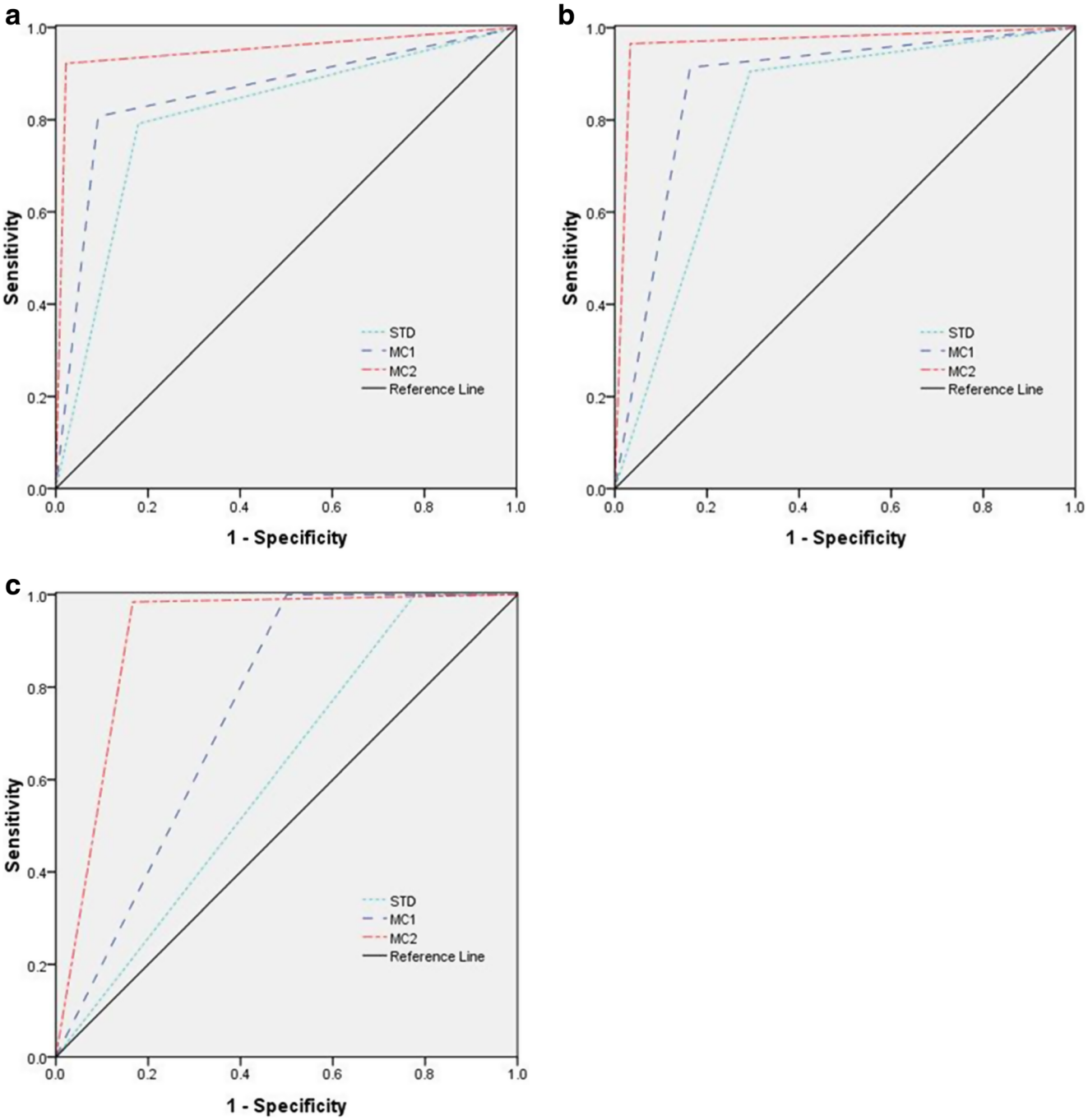

Fig. 2 The area under curves of the receiver-operating characteristic for detecting lumen stenosis ≥ 50% in 81 patients show results with standard, first-generation motion correction, and second-generation motion correction algorithm on per-segment (**a**), per-artery (**b**), and per-patient (**c**) levels, respectively

and 9 years of experience) who were not aware of the results of CCTA analysis. At least two orthogonal planes of each coronary segment were analyzed to identify stenosis, and additional planes were used whenever necessary. Lesions causing a 50% or greater reduction of the lumen were defined as significant stenosis. Consensus agreement was achieved for any disagreements.

The radiation dose of CCTA

The effective radiation dosage of CCTA was calculated in millisieverts using a modified CT dose index volume specific for the CT scanner. The estimated effective dosage was calculated as the dose-length product times a conversion factor for the chest $k = 0.014$ ($\mathrm{mSv} \times [\mathrm{mGy} \times \mathrm{cm}]^{-1}$) in the adult [19].

Table 4 Diagnostic value of CCTA with use of STD, MC1, and MC2 algorithms on per-segment, per-artery, and per-patient levels

Level	STD	MC1	MC2	*p* (STD v MC1)	*p* (STD v MC2)	*p* (MC1 v MC2)
Per-segment ($n = 1096$)						
Sensitivity -%(n/N)	79.2 (152/192)	80.7 (155/192)	92.2 (177/192)	0.720	< 0.001	0.001
Specificity -%(n/N)	82.1 (742/904)	90.8 (821/904)	97.8 (884/904)	< 0.001	< 0.001	< 0.001
PPV -%(n/N)	48.4 (152/314)	65.1 (155/238)	89.8 (177/197)	< 0.001	< 0.001	< 0.001
NPV -%(n/N)	94.9 (742/782)	95.7 (821/858)	98.3 (884/899)	0.439	< 0.001	0.001
Accuracy	81.5 (894/1096)	89.0 (976/1096)	96.8 (1061/1096)	< 0.001	< 0.001	< 0.001
AUC (ROC)	0.81	0.86	0.95	0.007	< 0.001	< 0.001
(95% CI)	(0.77–0.84)	(0.82–0.89)	(0.93–0.97)			
Per-artery ($n = 324$)						
Sensitivity -%(n/N)	90.5 (105/116)	91.4 (106/116)	96.6 (112/116)	1.000	0.016	0.070
Specificity -%(n/N)	70.7 (147/208)	83.7 (174/208)	96.6 (201/208)	< 0.001	< 0.001	< 0.001
PPV -%(n/N)	63.3 (105/166)	75.7 (106/140)	94.1 (112/119)	0.019	< 0.001	< 0.001
NPV -%(n/N)	93.0 (147/158)	94.6 (174/184)	98.1 (201/205)	0.558	0.017	0.066
Accuracy	77.7 (252/324)	86.4 (280/324)	96.6 (313/324)	< 0.001	< 0.001	< 0.001
AUC (ROC)	0.81	0.88	0.97	0.003	< 0.001	< 0.001
(95% CI)	(0.76–0.86)	(0.83–0.92)	(0.94–0.99)			
Per-patient ($n = 81$)						
Sensitivity -%(n/N)	100.0 (63/63)	100.0 (63/63)	100.0 (63/63)	> 1.000	> 1.000	> 1.000
Specificity -%(n/N)	22.2 (4/18)	50.0 (9/18)	77.8 (14/18)	0.125	0.001	0.031
PPV -%(n/N)	81.8 (63/77)	87.5 (63/72)	94.0 (63/67)	0.337	0.027	0.186
NPV -%(n/N)	100.0 (4/4)	100.0 (9/9)	100.0 (14/14)	1.000	1.000	1.000
Accuracy	82.7 (67/81)	88.9 (72/81)	95.1 (77/81)	0.125	0.006	0.125
AUC (ROC)	0.61	0.75	0.91	0.202	0.002	0.066
(95% CI)	(0.45–0.77)	(0.60–0.90)	(0.78–1.00)			

Values are represented as % (n/N)

The difference in sensitivity, specificity, and accuracy was test by McNemar's test

The difference in positive predictive value (PPV) and negative predictive value (NPV) was test by Fisher's exact test

The difference between the areas under curve was compared by comparing ROC curves using MedCalc.

STD standard, *MC1* first generation motion correction, *MC2* second-generation motion correction, *AUC* (*ROC*) area under the receiver operating characteristic curve, *CI* confidence interval

Statistical analysis

Quantitative variables including age, body mass index, heart rate, and heart rate variability were described as mean ± standard deviation. Categorical variables such as gender, hypertension, diabetes mellitus, and history of family CAD were expressed by frequencies and percentages. Image quality scores of the coronary artery segment were compared between any given pair of studied algorithms (STD vs. MC1, STD vs. MC2 and MC1 vs. MC2) by Wilcoxon matched pairs signed-ranks test. The Cohen κ was used to test inter-observer agreement in which κ values of 0.20 or less, 0.21–0.40, 0.41–0.60, 0.61–0.80, and 0.81 or more indicated poor, fair, moderate, good, and excellent agreement, respectively. The pair-wise McNemar or Fisher exact test was used to compare the difference in interpretability and diagnostic value between any given pair of studied image reconstruction algorithms including per-patient, per-artery, per-segment level, and three arteries. Statistical analysis was performed using SPSS software version 17.0. Furthermore, the area under the curve (AUC) value in the receiver operating characteristic analysis was calculated by Medcalc software version 15.6 to compare the difference in diagnostic performance between these three groups. A p value of less than 0.05 was considered as statistically significant.

Results

Study population characteristics

The mean age of patients was 58.7 ± 9.8 years (range, 31.0–76.0 years); 58.0% of participants were men; the mean body mass index was 24.8 ± 3.0 kg/m^2; and the mean interval delay between CCTA and ICA was 8.5 ± 6.4 days. Table 1 presents the characteristics of the study population. Radiation doses of CCTA and CT scanning parameters are shown in Table 2.

Table 5 Diagnostic value of CCTA in individual coronary arteries with use of STD, MC1, and MC2 algorithms

Artery	STD	MC1	MC2	*p* (STD v MC1)	*p* (STD v MC2)	*p* (MC1 v MC2)
LAD (*n* = 81)						
Sensitivity -%(n/N)	96.4 (53/55)	98.2 (54/55)	98.2 (55/56)	1.000	1.000	1.000
Specificity -%(n/N)	34.6 (9/26)	65.4 (17/26)	96.2 (25/26)	0.021	< 0.001	0.008
PPV -%(n/N)	75.7 (53/70)	85.7 (54/63)	98.2 (54/55)	0.147	< 0.001	0.019
NPV -%(n/N)	81.8 (9/11)	94.4 (17/18)	96.2 (25/26)	0.539	0.205	1.000
Accuracy	76.5(62/81)	87.7(71/81)	97.5(79/81)	0.012	< 0.001	0.021
AUC (ROC)	0.66	0.82	0.97	0.014	< 0.001	0.013
(95% CI)	(0.52–0.79)	(0.70–0.94)	(0.00–1.00)			
LCX (*n* = 81)						
Sensitivity -%(n/N)	88.5 (23/26)	88.5 (23/26)	100.0 (26/26)	1.000	> 1.000	> 1.000
Specificity -%(n/N)	56.4 (31/55)	70.9 (39/55)	96.4 (53/55)	0.039	< 0.001	< 0.001
PPV -%(n/N)	48.9 (23/47)	59.0 (23/39)	92.8 (26/28)	0.353	< 0.001	0.002
NPV -%(n/N)	91.2 (31/34)	92.9 (39/42)	100.0 (53/53)	1.000	0.294	0.316
Accuracy	66.7 (54/81)	76.5 (62/81)	97.5 (79/81)	0.077	< 0.001	< 0.001
AUC (ROC)	0.72	0.80	0.98	0.142	< 0.001	< 0.001
(95% CI)	(0.61–0.84)	(0.69–0.90)	(0.00–1.00)			
RCA (*n* = 81)						
Sensitivity -%(n/N)	90.3 (28/31)	93.6 (29/31)	96.8 (30/31)	1.000	0.500	1.000
Specificity -%(n/N)	64.0 (32/50)	82.0 (41/50)	92.0 (46/50)	0.022	< 0.001	0.063
PPV -%(n/N)	60.9 (28/46)	76.3 (29/38)	88.2 (30/34)	0.131	0.007	0.189
NPV -%(n/N)	91.4 (32/35)	95.4 (41/43)	97.9 (46/47)	0.652	0.308	0.604
Accuracy	74.1 (60/81)	86.4 (70/81)	93.8 (76/81)	0.013	< 0.001	0.031
AUC (ROC)	0.77	0.88	0.94	0.005	< 0.001	0.014
(95% CI)	(0.67~0.88)	(0.80~0.96)	(0.89–1.00)			

Values are represented as % (n/N)

The difference in sensitivity, specificity, and accuracy was test by McNemar's test

The difference in positive predictive value (PPV) and negative predictive value (NPV) was test by Fisher's exact test

The difference between the areas under curve was compared through the comparison of ROC curve using MedCalc.

STD standard, *MC1* first generation motion correction, *MC2* second-generation motion correction, *LAD* left anterior descending artery, *LCX* left circumflex artery, *RCA* right coronary artery, *AUC* (*ROC*) area under the receiver operating characteristic curve, *CI* confidence interval

Image quality and interpretability

A total of 1096 coronary segments were assessed using STD, MC1, and MC2 reconstructions. Three hundred sixty-two coronary segments were missed because of anatomical variants, such as a diameter less than 1.5 mm or a length shorter than 15 mm. Inter-observer agreement for the image quality score was evaluated in the STD, MC1, and MC2 groups with Kappa = 0.764, 0.786, and 0.800, respectively. This indicates a good agreement. Overall, the mean image quality score and interpretability were 2.81 ± 0.85 and 92.5%, 3.21 ± 0.79 and 97.2%, 3.56 ± 0.63 and 99.2% using STD, MC, and MC2 algorithms on per-segment level, respectively. In comparison with STD and MC1, the use of MC2 was associated with statistically significant improvements in image quality scores and interpretability on a per-segment, per-vessel, and per-patient levels, except in following comparisons: per-vessel interpretability between MC1 and MC2 in the right coronary artery (RCA) and per-vessel interpretability between STD and MC1, STD and MC2, and MC1 and MC2 in the left main artery. Detailed comparisons between STD, MC1, and MC2 algorithms are shown in Table 3.

Diagnostic performance of CCTA among STD, MC1, and MC2

In this study, a high prevalence of stenosis (77.8%) was observed on the per-patient level. MC2 showed significant improvements over STD and MC1 in terms of sensitivity, specificity, PPV, NPV, and accuracy on the per-segment level and specificity, PPV, and accuracy on the per-vessel level. On the per-patient level, specificity, PPV, and accuracy showed significant improvements with MC2 compared to STD; however, no significant difference was observed between STD and MC1. Significant differences were found in the diagnostic

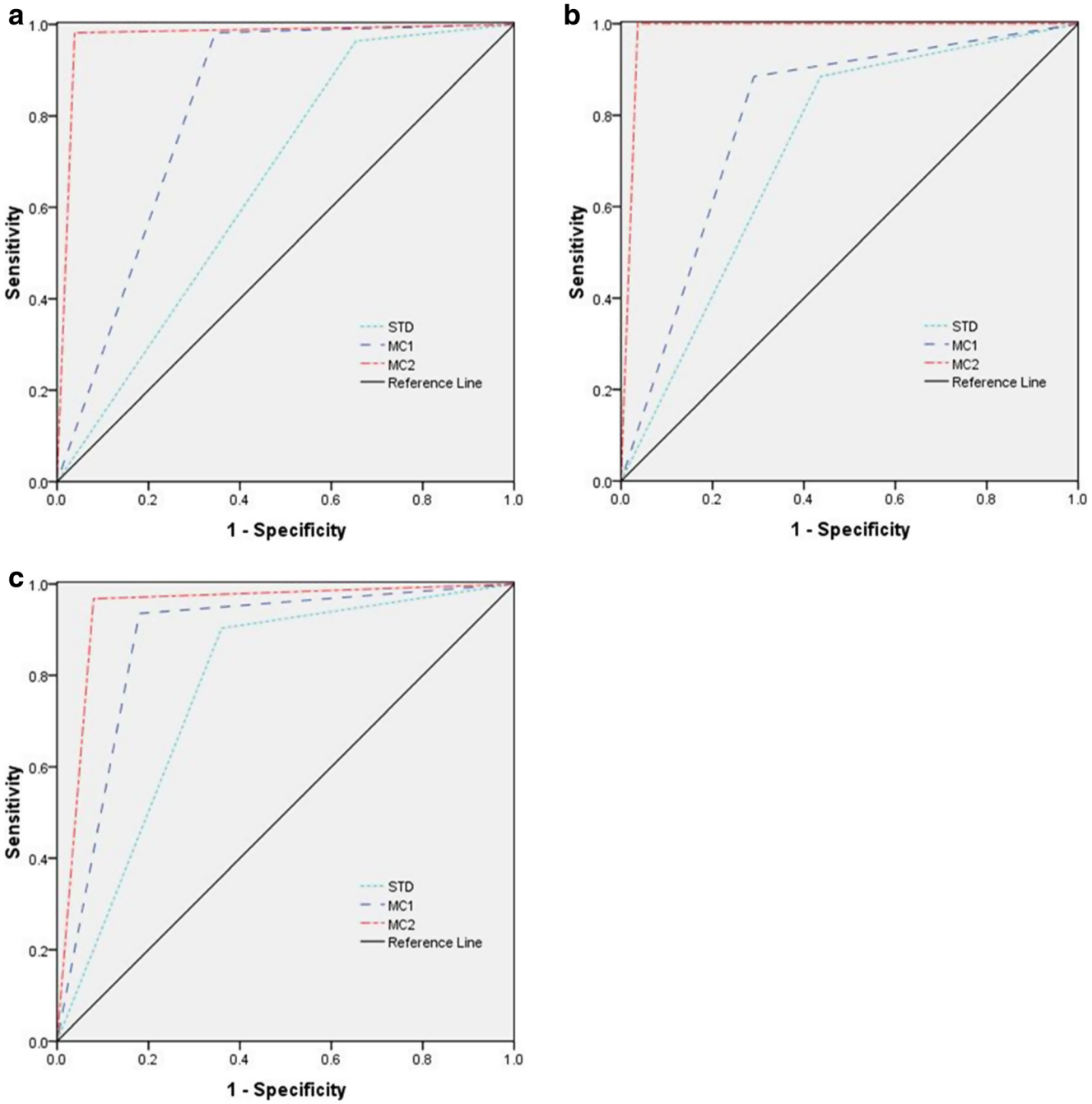

Fig. 3 The area under curves of the receiver-operating characteristic for detecting lumen stenosis ≥ 50% in 81 patients show results with standard, first-generation motion correction, and second-generation motion correction algorithm on the left anterior descending coronary artery (**a**), left circumflex coronary artery (**b**), and right coronary artery (**c**)

performance using MC2 compared to STD and MC1, with AUC being 0.95 versus 0.81 and 0.86 on the per-segment level; 0.97 versus 0.81 and 0.88 on the per-vessel level and 0.91 versus 0.61 and 0.75 on the per-patient level (Fig. 2). Table 4 shows the diagnostic performance in the STD, MC1, and MC2 groups. The number of false positive decreased significantly after using MC2 algorithm on the per-segment, per-vessel, and per-patient levels.

The diagnostic performance of CCTA in LAD, RCA, and LCX between STD, MC1, and MC2 algorithms was compared using ICA as reference standard and shown in Table 5. In summary, the application of MC2 algorithm is associated with improvements in accuracy, specificity, and PPV for LAD and LCX when compared to both STD and MC1 and improvements in accuracy, specificity, and PPV for RCA when compared to STD. Moreover, in case of three main coronary

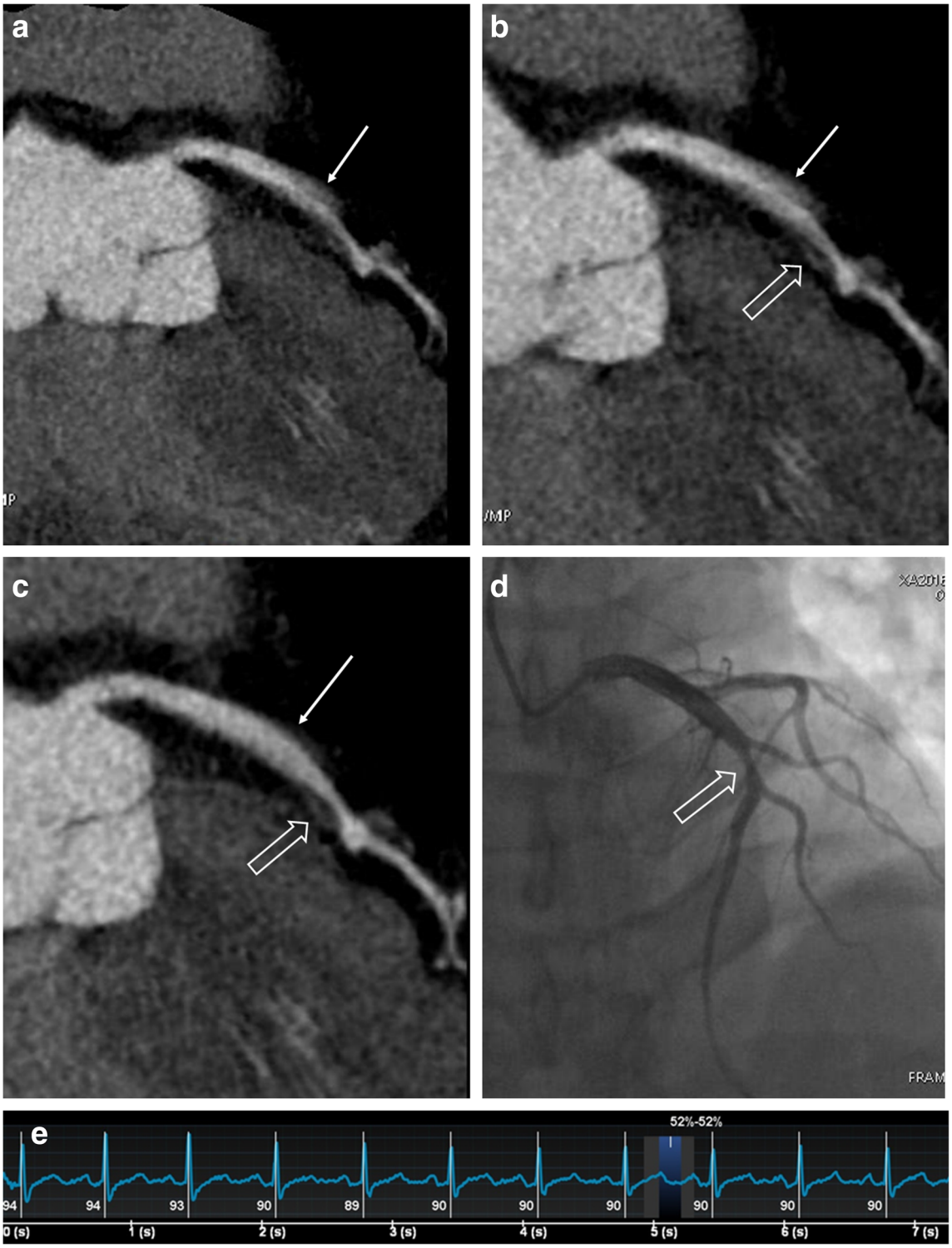

Fig. 4 A 63-year-old man with a body mass index of 28.69 kg/m^2 was suspected with coronary artery disease. The effective dose from coronary CT angiography was 0.86 mSv. Curved multi-planar reformats image (**a**) with standard algorithm shows motion artifacts *(arrow)* and affect the significant stenosis at mid-segment of left anterior descending (LAD). Image (**b**) with MC1 shows less motion artifacts *(arrow)* and suspected stenosis *(open arrow)*. Image (**c**) with MC2 shows no motion artifacts *(arrow)* and significant stenosis *(open arrow)*. Images **a**, **b**, and **c** are in the same angle. Invasive coronary angiography (**d**) confirms significant stenosis *(open arrow)*. ECG report (**e**) shows that the heart rate was 90 bpm

arteries, AUC showed a significant improvement in the MC2 group when compared to both STD and MC1 algorithms with AUC being 0.97 versus 0.66, 0.82 for LAD; 0.98 versus 0.72, 0.80 for LCX and 0.94 versus 0.77, 0.88 for RCA, respectively

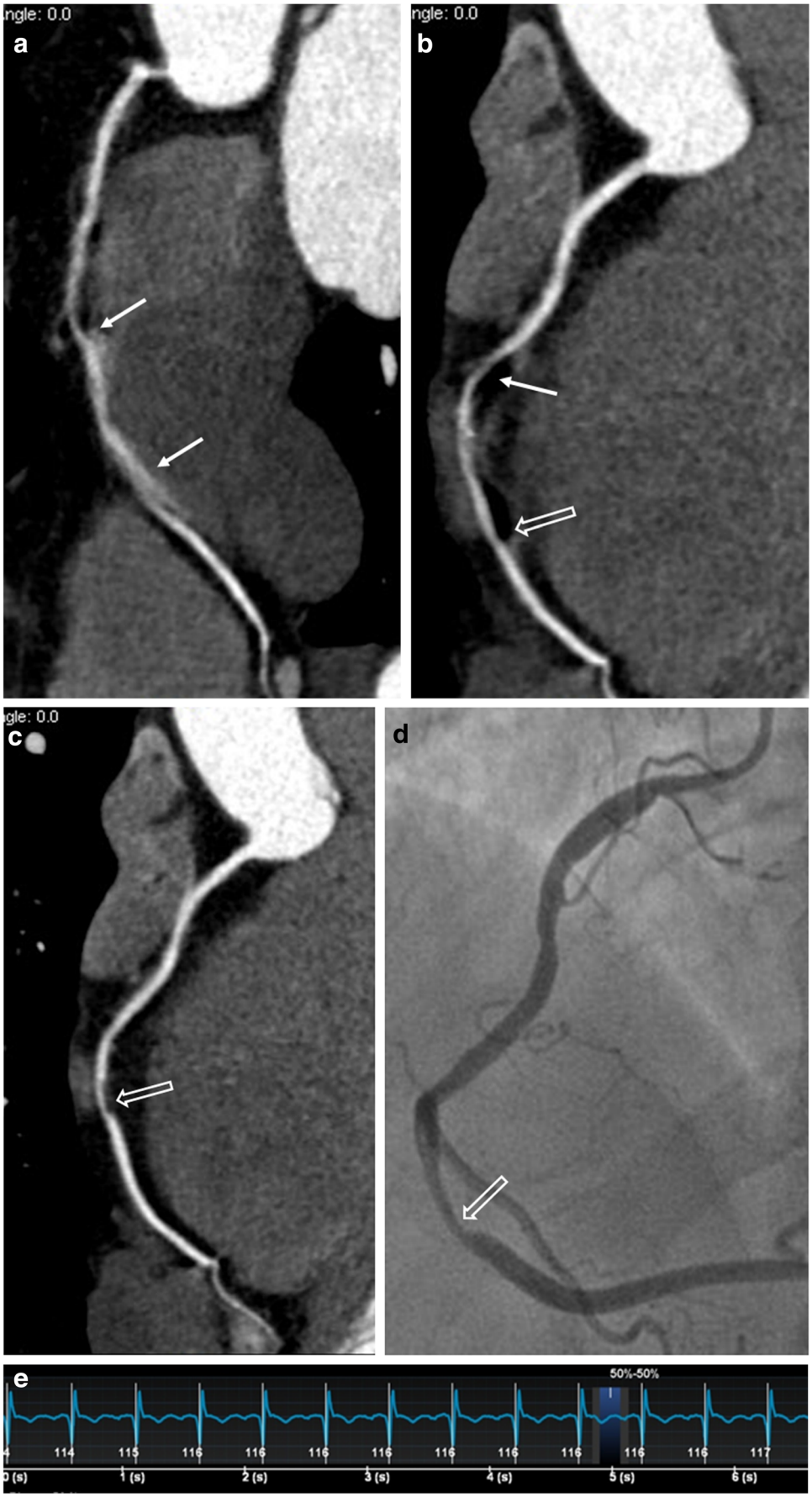
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Fig. 5 A 65-year-old woman with a body mass index of 20.43 kg/m^2 was suspected with coronary artery disease. The effective dose from CCTA was 1.01 mSv. Curved multi-planar reformats image (**a**) with standard algorithm was non-interpretable due to motion artifacts at the mid *(arrow)* and distal *(arrow)* segments of the right coronary artery (RCA). Image (**b**) using MC1 shows suspected stenosis *(arrow and open arrow)* at the RCA because of motion artifacts. Image (**c**) using MC2 shows a non-calcified plaque with stenosis at the distal segment of RCA *(open arrow)*. ICA (**d**) shows significant stenosis *(open arrow)* at the distal segment of RCA. ECG report (**e**) shows that the heart rate was 116 bpm

(Fig. 3). Figures 4 and 5 provide information on STD, MC1, and MC2 algorithm reconstructions in two patients with coronary artery luminal stenosis and associated elevated heart rates.

Discussion

Our study demonstrates significant improvement in image quality and reduction of the number of non-diagnostic segments using MC2 algorithm over STD and MC1. The interpretability of coronary segments with MC2 was higher on the per-segment, per-artery, and per-patient levels compared to STD and MC1. High accuracy of CCTA was achieved using MC2 in the assessment of all studied coronary arteries.

MC1 algorithm has been first reported by Leipsic et al [17]. Several studies have reported that MC1 improved image quality and coronary interpretability [20–23], in addition to improving diagnostic accuracy [24, 25] using a 64-slice or a latest 256 detector row CT. However, even with MC1 algorithm, several false positive segments still exist due to motion artifacts, reducing diagnostic accuracy [11] particularly when calcifications were present [26]. In this study, we showed the superiority of the MC2 algorithm over both MC1 algorithm as well as standard (non-corrected) images in a group of patients with elevated heart rates. Our study also agreed with previous reports showing no significant difference in diagnostic accuracy on per-patient analysis between STD and MC1 algorithm [17, 27]. However, our study revealed that the MC2 significantly improved the specificity, PPV, and accuracy on per-patient level when compared to STD.

Concerning RCA, we also found an improvement in specificity and accuracy using MC1 compared to STD, which is in accordance with the results from Lee and Liang [21, 24]. Moreover, the specificity, PPV, and accuracy were improved by MC2 algorithm when compared to STD. Additionally, the specificity and accuracy improved with MC2 compared to MC1. Similarly, for LAD and LCX, the accuracy, specificity, and PPV were significantly improved by MC2 when compared to STD and MC1. However, no difference was found between STD and MC1 for LCX, excepting specificity. From these findings, it appears that MC1 algorithm is most effective in correcting motion in RCA where motion velocity is greatest and motion artifacts occur more often [20, 27, 28]. MC2 not only worked well in correcting motion in the RCA but also provided significant improvement in the image quality and accuracy in LAD and LCX when compared to MC1. A previous study has reported that MC2 algorithm extends motion correction to the whole heart in a single cardiac cycle scan [14, 29]; however, both of these studies focused mainly on cardiac valve abnormalities.

With the development of hardware and application of MC1 algorithm in this latest 256-detector row CT system, CCTA can be performed in patients with increased heart rates in one heartbeat with low radiation dose [11, 12]. The mean effective dose of all patients in the current study was 1.0 mSv, which was lower than those in the abovementioned studies. The dose level in our study was similar to that from Tang et al [28] and lower than Koplay et al [30]; both of these studies have used a dual-source CT scanner in patients with increased heart rates.

In this study, we only included patients with heart rate variability (HRV) less than 20 bpm. HRV is a factor that affects the image quality and diagnostic accuracy of CCTA, and it is more pronounced when using narrow-detector CT systems that require several heartbeats to cover the entire heart. Leschka et al [31] have found that HRV definitely correlates with mean image quality and has a negative relationship with the diagnostic accuracy when using a 64-slice CT. However, the impact of HRV on the image quality or diagnostic accuracy is much less pronounced when the heart is scanned in one heartbeat. Matt et al [32] have shown that HRV has no significant effect on the image quality in any segment when using a dual-source CT scanner. A study by Brodoefel et al [33] involving a dual-source CT scanner has found that inter-examination HRV has a persistent effect on the image quality but no impact on the diagnostic accuracy. Similarly, Muenzel et al [9] have shown that there is no significant effect of HRV on motion artifacts, when using a 256-slice CT. In addition, a latest study by Chen et al [10] has reported that image quality scores are not statistically different between patients with HRV less than 10 bpm and more than 10 bpm, when using a 160 mm detector CT. Since our study was performed using a 160 mm detector CT scanner that covers the entire heart in one heartbeat, and because the main purpose of the study was to compare different reconstruction algorithms using same patient scan data, we anticipated that the HRV would have less impact on the study results, and the study findings were limited to patients with HRV less than 20 bpm.

Several limitations need to be acknowledged in this research. Our research should be perceived as a pilot study with a small sample size based on a single-center experience. A large number of patients including patients with HRV $\geq$ 20 bpm, irregular heart rates, and atrial fibrillation were excluded in the present research. This may introduce bias to the present conclusions. Therefore, further studies are needed to include a broader pool of patients before the conclusions can be generalized.

Secondly, coronary artery calcium scoring was not available in this study, since the purpose of the study was to assess the image quality, interpretability, and diagnostic performance of single heartbeat CCTA with the use of STD, MC1, and MC2 algorithms. The presence of severe coronary artery calcification could reduce the accuracy of significant luminal stenosis assessment. Further research is needed to evaluate if MC2 still performs better than STD and MC1 in the presence of heavy coronary calcification. Thirdly, a high prevalence of coronary artery stenosis could affect the image analysis and diagnostic performance. According to the guidelines, CCTA should be performed in patients with low to intermediate pretest probability of CAD. Thus, future studies should consider the impact of disease prevalence on these findings. In addition, the MC2 algorithm assessed in this research is currently vendor-specific.

Conclusion

In conclusion, our findings suggest that the MC2 algorithm improves image quality and reduces motion artifacts compared to both MC1 and STD algorithm.

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Compliance with ethical standards

Guarantor The scientific guarantor of this publication is Lei Xu.

Conflict of interest The authors of this manuscript declare relationships with the following companies: GE Healthcare.

Statistics and biometry One of the authors has significant statistical expertise.

Informed consent Written informed consent was obtained from all subjects (patients) in this study.

Ethical approval Institutional Review Board approval was obtained.

Methodology
- prospective
- diagnostic study
- performed at one institution

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